# EVALUATION OF THE HETEROTIC POTENTIAL OF SORGHUM [*Sorghum bicolor* (L.) Moench] ADAPTED TO THE SOUTHERN AFRICA REGION

A Thesis

by

LEO THOKOZA MPOFU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Plant Breeding

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Approved by:

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## ABSTRACT

Evaluation of the Heterotic Potential of Sorghum [*Sorghum bicolor* (L.) Moench]

Adapted to the Southern Africa Region. (December 2005)

Leo Thokoza Mpofu, B.Sc., University of Zimbabwe

Chair of Advisory Committee: Dr William L. Rooney

Sorghum [*Sorghum bicolor* (L.) Moench] production in Africa is widespread with low yields due to low inputs and the lack of sorghum hybrids. This situation has forced most of these farmers to grow maize hybrids since they are readily available in the seed market. Sorghum hybrids could be used if their potential was demonstrated. The objective of this study is to document the level of heterosis in Southern Africa sorghum germplasm.

The performance of 52 $F_1$ grain sorghum hybrids and their parental lines was evaluated in four environments. Measurements for grain yield, panicle exsertion, days to mid anthesis and plant height were analyzed to obtain estimates of high parent heterosis. High parent heterosis was observed to be 37.18% for yield, 82.77% for exsertion, -0.02% for days to mid anthesis and 23.7% for height.

ICSR-939 and (87EON366*90EON328)-LD30 can be used as testers to develop more female lines for further hybrid seed production in breeding programs because they had the highest general combining ability. Protein content averaged 11.69%. ATx635 had significantly higher protein content than ATx631 (13.49% compared to 9.69%, respectively) and its hybrids had more protein than ATx631 hybrids (11.6% compared to

10.67% for ATx631). Mean heterosis for protein content was negative at –12.5%. This shows that hybrids had lower protein content than their parents since protein content is negatively correlated to grain yield (-0.35**). Starch content averaged 72.13% and ATx631 hybrids had more starch than ATx635 hybrids (73.16 compared to 72.37% respectively).

Two hybrids, ATx.631/(87EON366*90EON328)-LD30 and ATx631/ ((TAM428*SV1)*CE151)-LD3 had the highest yields (5.04 t/ha and 4.93 t/ha, respectively). These hybrids also had small grains with good hardness and acceptable whiteness. They had good exsertion, flowered in good time and had acceptable plant heights. These two hybrids were compared to regional check varieties Macia and Tegemeo for all traits and they were either superior or within an acceptable range. These two hybrids are therefore recommended for release in the region.

There is need therefore to start working on the various components of seed systems in the region so that seed of these two hybrids is made available to farmers who need the seed.

## DEDICATION

To my father Elliot Mpofu. I wish you were here to see me. Wherever you are, I know you are proud of me.

May your soul rest in peace and GOD bless you!!!

## ACKNOWLEDGEMENTS

I would like to thank Dr. Bill Rooney for his guidance in my studies at Texas A&M University. His willingness to share knowledge and experience will forever be cherished and I hope he will maintain the same spirit throughout.

I would like to thank Dr. Gary Peterson too for all the effort he put to get me to come to the US and study amid all the problems. My thanks also go to the staff at INTSORMIL Nebraska for the funding and smooth collaboration we have had over the years.

In Zambia, I would like to thank Dr. Medson Chisi and his team for hosting my experiment. To Mr. Delroy Collins and Karen Prihoda, this research would not be complete without your input. My gratitude also extends to the technicians at Lubbock and Weslaco.

I also thank Dr. Lloyd Rooney and his team for letting me use their lab for food quality analysis. My special thanks to all fellow students in the sorghum breeding team, namely, Joaquim Mutaliano, Les Kulman, Rafael Mateo, Gabriel Krishnamoorthy and Ryan Bading for their help. Thanks to Mr. Bill Liles and Stephen Labar for their assistance.

Finally, thanks to my parents Elliot Mpofu and Ellen Ncube for bringing me into this wonderful world.

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# CHAPTER I

# INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is a cultivated tropical cereal grass. It ranks fifth among the world's cereals following wheat, maize, rice and barley in terms of production (FAO, 2004). Sorghum is African in origin, but its domestication may have taken place in multiple locations within the continent (Kimber, 2000). The domestication of sorghum in Africa has made sorghum uniquely adapted to Africa's climate, being both drought and heat resistant, but also able to withstand periods of water logging. The largest diversity of cultivated and wild sorghum is in Africa (Doggett, 1970; De Wet and Harlan, 1971).

For some of the world's most food insecure people sorghum remains the only viable food grain. Average grain yield for sorghum in most areas of Africa is below 1 t/ha (Chisi, 1996). Most countries in the Southern Africa region produce very low yields (Figure 1). Sorghum yield in this region is below the world average with South Africa recording the highest average at 3.45 t/ha. The high yields in South Africa result from sorghum hybrid grown in the commercial sector. For the rest of the region the low average yield is due primarily to sorghum cultivation being characterized by traditional farming practices with minimal inputs (no inorganic fertilizer or pesticides) and traditional varieties or landraces. Biotic and abiotic stresses such as high temperature, low and erratic rainfall, poor soils, pests and diseases are predominant in these areas of Africa.

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This thesis follows the style of Crop Science.

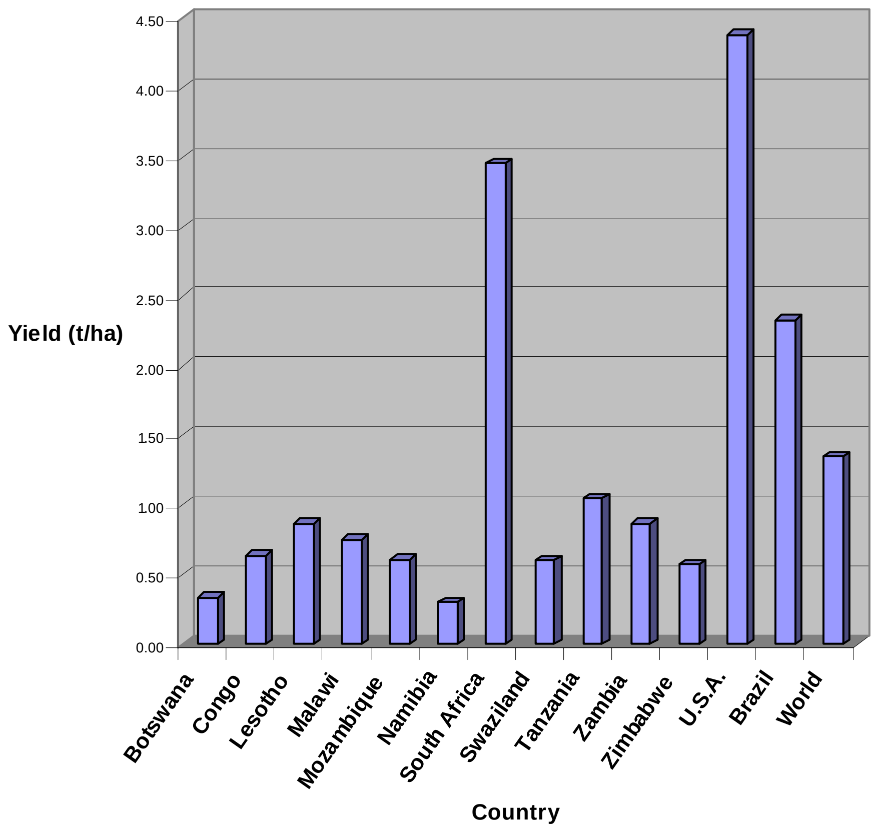


**Figure 1.** Sorghum yields in tons per hectare for eleven Southern African countries in 2004 contrasted with the world average and the U.S. and Brazil averages. (Source: www.fao.org)

Research has been done to assess the need and potential in the developing world for sorghum hybrid development and utilization [House et al., 1996; Obilana et al., 1996]. When compared to improved and landrace varieties, sorghum hybrids have shown a yield advantage in the range of 20 to 60%. In the Southern Africa region, the Southern Africa Development Community/International Crop Research Institute for the Semi Arid Tropics (SADC/ICRISAT) Sorghum and Millet Improvement Program (SMIP) in collaboration with the National Agriculture Research Scientists (NARS) released 1 sorghum hybrid in Botswana, 3 in Zambia and 1 in Zimbabwe by 1996. Several improved varieties were also released in other Southern African countries as well. In most of the countries in this region there is very little private sector participation in sorghum research except for South Africa. Most national sorghum breeding programs in the region focus on development of open pollinated varieties with less emphasis on hybrids as this is the perceived need in the region. Chisi (1996) stated that most farmers in the Southern Africa region still grow local land race varieties that are characterized by late maturity, poor harvest index, variable plant height, susceptibility to diseases and pests such as downy mildew, head smut, anthracnose, shoot fly and armored crickets. Lack of good seed systems for sorghum hybrids and improved variety seed has been the cause for poor adoption.

However, many farmers in the region have adopted and grow maize hybrids even though there is much higher risk of crop loss with maize as compared to sorghum. This has resulted in two anomalies which should in the long-term benefit sorghum. First, maize often fails to produce due to heat and drought stress and local farmers have to rely on food handouts from relief agencies. Additionally, there is less grain to sell in urban markets. Secondly, the use of sorghum cultivars and maize hybrids has led to the concept that sorghum hybrids are either not possible or not competitive in production with maize hybrids. Thus if it can be demonstrated that farmers can successfully grow and market sorghum hybrids the growth potential for sorghum and associated economic development will be excellent.

Another obstacle to sorghum hybrid production in the Southern Africa region is the lack of a viable hybrid sorghum seed production system similar to what exists for maize and other commercial crops (including brewing-type sorghum). The existence of a viable seed system for brewing type sorghum suggests that the same could be done for food type sorghum only if food type sorghum is commercialized like brewing type sorghum. The availability of high-yielding hybrids with improved grain quality paves the way for establishing a viable hybrid sorghum seed industry. If farmers can pay for hybrid seed maize and other crops, and sorghum hybrids are documented to have high yield and good quality, it is more likely that they will pay for hybrid sorghum suitable for rain-fed production. However, it is necessary to determine what potential value sorghum hybrids have in the region given their yield potential and grain quality.

Since hybrid sorghum production is feasible, it is important to document the agronomic productivity of hybrid sorghum in Southern Africa. The commercial sorghum beer brewing industry has an excellent conceptual framework for introducing hybrids with improved grain yield potential and grain quality. Private seed companies and beer companies network in contracting farmers to grow brown or red grain brewing type sorghum hybrids for their markets. These sorghum hybrids produce high yields that are competitive enough to attract a large number of farmers to satisfy that market. The availability of seed of good hybrids and a lucrative market play a major role in this system. A new market venture in Zambia using this system is contracting for white seed sorghum for use in production of a lager-base sorghum beer.

Because sorghum is used as a food in this region grain quality for food use must be considered. In most countries the grain is first milled into flour and used to make thick porridge (Sadza/Isitshwala in Zimbabwe, Uphuthu in South Africa and Nsima/Nshima in Zambia, Malawi and Mozambique) to be taken with vegetables and or meat. Some whole grain products (Umcaba- mixture of whole grain sorghum with sour milk) also exist although others dehull the grain first with mortar and pestle. It is therefore important that new hybrids express good milling qualities and the sorghum paste should have good texture. Nutritive value and taste cannot be over emphasized since babies and sick people rely on sorghum as a primary source of calories. Many traditional and improved landrace varieties do not have good food quality traits. This is a contributing factor to their low adoption rates. Other important traits include plant and grain color, grain hardness, milling properties, tannin content and nutrient content among others.

The objectives of this research are to (1) determine the amount of heterosis present in elite sorghum inbred lines and cultivars adapted to Southern Africa when they are in hybrid combination (2) determine the grain quality of sorghum hybrids produced from elite inbred lines and cultivars from Southern Africa, and (3) identify which specific hybrid combinations have the most promise for Southern Africa.

# CHAPTER II

# LITERATURE REVIEW

## The importance of sorghum

Sorghum is a crop that can grow in the very dry and poor soil conditions that dominate most parts of the developing world. The mechanisms that enable this crop to survive under these harsh conditions are complex and not well understood. Previous researches suggest three general strategies for plant survival in drought environments [Turner, 1979; Jordan and Monk, 1980; Ludlow and Muchow, 1990]. These strategies are drought escape, avoidance, or tolerance. Drought escape happens when a plant grows and completes its life cycle before soil moisture becomes limiting. Drought avoidance is a mechanism by which plants maintain positive tissue water relations even under limited soil moisture conditions. This is achieved by decreasing water loss from the shoot or by more efficient extraction of moisture from the soil. Drought tolerance mechanisms are more complex and function at the tissue or cellular level. These mechanisms stabilize and protect cellular and metabolic integrity. Sorghum utilizes any one or combinations of these mechanisms at varying levels depending on the timing of the drought and hence can survive in areas with an annual rainfall in the range of 500-700 mm per year where many crops would fail. With continued water scarcity in many areas of the world there is the need to increase water productivity through the use of water-use efficient crops like sorghum under irrigated or rain-fed conditions.

Today in Africa sorghum is grown mostly for subsistence by farmers who seldom have any surplus to sell. Beyond Africa sorghum production is increasing mainly due to farmers who sell their grain in commercial markets. As a continent, Africa is the largest producer of sorghum with approximately 18.5 million metric tons produced annually (U.S. Grains Council Website; 9/26/05). The United States is currently the number one single producer (9.3 million metric tons) and exporter of sorghum on the world market with most of the exports going to Mexico. India and Nigeria are the second and third largest producers. For exports Australia and Argentina are second and third, respectively. Sorghum is used predominantly as a feed grain in developed countries and as a food grain in less developed countries. A significant amount of research has been done on desired food quality aspects of sorghum that are acceptable to both consumers and industry (Hulse et al., 1980; Rooney and Murty (Eds). 1981; Rooney and Murty. 1982; Badi et al., 1990; Dendy, 1995). Most (but not all) food-type sorghums have white pericarp, tan plant color, straw color glumes, and produce grain with medium to hard endosperm kernels (Rooney and Waniska. 2000). Carbohydrates constitute the largest part of sorghum grain at 70 to 90 % (Hulse et al., 1980). Protein content is very variable ranging from 7.1 to 14.2% with values as high as 21.5% reported. The variation is caused by factors such as planting date, cultivar, seed size, and air temperature (Burleson et al, 1956).

Pushpamma and Vogel (1981) described some negatives about sorghum although some of these negatives can be considered favorable as well. Sorghum, like all other cereal grains, contains some polyphenolic compounds that can discolor sorghum food products. However, the same compounds have been shown to have antioxidant properties (Awika et al., 2003). Grain sorghum has become more popular in developed societies because it is gluten-free and provides an alternative cereal grain for individuals who are allergic to gluten and cannot consume wheat or products made from wheat. Some sorghums contain condensed tannins (proanthocyanidins) that can bind the grain proteins with the enzymes of the digestive tract reducing the nutritional value of the grain. The same tannins also offer resistance against bird, insect and fungal attack. However not all sorghums contain tannins.

In the United States, grain sorghum is most commonly used as livestock feed for cattle (both beef and dairy), poultry, pigs, lambs, horses, catfish and shrimp (Syngenta website 09/26/05). The grain has numerous other industrial uses such as making foundry-mold sands, charcoal briquets and oil well mud. Sorghum flour is used in the manufacture of plywood and gypsum to build houses as well as in the refining process of potash and aluminum.

When used as a feed grain, the relative feed value of sorghum is 96 to 98% that of maize while its price is usually 10 to 15% cheaper than maize (Hancock, 2000). The concentration of most minerals is greater in sorghum than maize. Processing methods such as grinding, crushing, steaming, steam flaking, popping and extrusion are used to enhance the nutritive value of the grain for feeding.

Throughout sub-Saharan Africa sorghum is the grain of choice to produce traditional cloudy and opaque (sorghum) beers. This beer is a useful potential source of vitamins especially thiamin, riboflavin and nicotinic acid (Westhuyzen et al., 1985). Taylor (2003) reviewed fermented foods and beverages from sorghum grain in Southern Africa. The ingredients needed in the sorghum beer making process are sorghum malt, which provides hydrolytic enzymes (especially amylases to ferment sugars into ethanol and carbon dioxide), starch (the source of fermentable sugars), yeast nutrients and beer flavor and color substances. Total opaque beer production in Southern and Eastern Africa is around 1,700 million litres per year. South Africa alone has 24 commercial breweries. There are indications, however, that perhaps at least twice this volume of beer is home-brewed using commercially manufactured sorghum malt. In Botswana industrial sorghum beer production has been growing rapidly at around 5% per year. However, in some countries, notably South Africa, there is strong evidence that as consumers become more affluent they drink lager beer in preference to sorghum beer.

In the U.S. ethanol is blended in 30% of the country's gasoline (Kansas Grain Sorghum Producers Association website. 09/26/05). An annual record of 3.41 billion gallons of ethanol was produced in the U.S. in 2004. Most of this was produced from maize but sorghum grain and juice from sweet sorghum is fast gaining popularity.

## The concept of heterosis

Shull (1952) first used the term heterosis in 1914 to explain superiority over the best parent for grain yield. Heterosis has been widely used in breeding programs for the identification of genetically divergent populations as a base for the development of inbred lines to be used in hybrid crosses (Hallauer, 1990). Expression of heterosis in population or line crosses requires two conditions: (i) dominance at loci controlling the trait of interest (ii) differing allele frequencies at those loci in the populations or lines involved in the crosses (Falconer and Mackay, 1996).

Today, the terms hybrid vigor and heterosis are usually used synonymously to describe the beneficial effects of hybridization. There are two ways of calculating heterosis:

$$\text{Mid-parent heterosis} = \left[\frac{F_1 - (P_1 + P_2)/2}{(P_1 + P_2)/2}\right] * 100$$

$$\text{High-parent heterosis} = \left[\frac{F_1 - HP}{HP}\right] * 100$$

Where $F_1$ = Mean of the $F_1$ offspring/hybrid

$P_1$ = Mean of parent 1

$P_2$ = Mean of parent 2

HP = Mean of highest performing parent

High parent heterosis is of more practical and applicable use to make fast significant gains in the trait of interest. It shows the performance of the hybrid in comparison with the best parent unlike mid-parent heterosis that compares the hybrid with the mean of the two parents. The mean of the two parents is always lower than the mean of the best parent.

Two major hypotheses have been promulgated to explain this phenomenon: the dominance hypothesis and the overdominance hypothesis. The dominance hypothesis, proposed by Davenport (1908), Bruce (1910), and Keeble and Pellew (1910), and later elaborated by Jones (1917), suggests that heterosis is due to the canceling of deleterious recessives contributed by one parent by dominant alleles contributed by the other parent in the heterozygous $F_1$. The overdominance hypothesis, proposed by East (1908), suggests that the heterozygous combination of the alleles at a single locus is superior to either of the homozygous combinations of the alleles at that locus.

The dominance hypothesis seems to be more popular with most scientists in recent years [Carr and Dudash, 2003: Hua et al., 2003: Xiao et al., 1995]. There has been strong argument against the overdominance hypothesis as stated by Charlesworth and Charlesworth (1999) who concluded that overdominance effects were unimportant in most cases. However, using molecular marker-based studies in crops like maize (Stuber et al., 1992; Cockerham and Zeng, 1996), rice (Yu et al., 1997; Li et al., 2001; Luo et al., 2001) have suggested overdominance to be important, although the possibility of the presence of pseudo-dominance effects in these studies could not be ruled out (Carr and Dudash, 2003). These studies also showed that epistasis plays a considerable role in the phenomenon of heterosis.

**Heterosis in sorghum**

Heterosis in grain yield and other agronomic traits has been shown to exist in a wide variety of crops. Siles et al., (2004) reported 67% $F_1$ heterosis of yield in foxtail millet. In both rice and wheat, the maximum heterosis for grain yield has been approximately 20% (Virmani, 1999; Jordaan et al., 1999). Axtell et al., (1999) reported a 20 to 30% heterosis in the cross-pollinated species pearl millet. In sorghum, heterosis for yield has been reported to range from 39 to 80% (Quinby, 1962). Hybrid vigor or heterosis is explained on a basis of gene action.  Quinby et al., (1946) indicated that fewer genes than in maize may be involved in heterosis in sorghum. Quinby and Martin

(1954) and Quinby and Karper (1963) indicated that heterosis in sorghum involves complementary action of alleles as well as complementary action of non-allelic genes. From his work on maize, Kiesselbach (1922) concluded that 90% of the heterosis in hybrids came from increased number of cells and 10% from increased size of cells. There is reason to think that the same relationship exists in sorghum. After comparing hybrids and their parents, (Quinby, 1962) found that heterosis in sorghum is expressed by earlier blooming, increased height, more tillering, larger stems, larger heads, higher threshing percentage, and greater production of grain and forage. Larger heads of hybrids indicate that heterosis was particularly effective in increasing cell number during the period following floral initiation when seed branches and spikelets were being formed and this leads to more seeds per head of sorghum.

In his work on maize (Ordas, 1991) proved that the amount of heterosis shown by a hybrid depends largely on the genetic divergence of the parental varieties from which the inbreds have been extracted. The more divergent the parents, the higher the degree of heterozygosity and heterosis. Establishment of heterotic patterns among varieties helps breeders to plan experimental crosses. For this reason genotypes are often grouped into heterotic groups. A heterotic group comprises a set of genotypes that perform well when crossed with genotypes from a different heterotic group (Hallauer et al., 1988). Members of the same heterotic group do not produce high heterosis or hybrid vigor.

In sorghum, heterotic groups have been defined by the milo-kafir cytoplasmic genetic male-sterility system where lines are grouped on whether they are A/B-lines (female parent group with A-1 cytoplasm and lacking the fertility restoring gene) or R-lines (male parent group with normal cytoplasm and fertility restoring genes) (Stephens and Holland, 1954; Quinby and Martin, 1954). New germplasm is placed in one of these two groups depending on whether or not it possesses fertility-restoring genes. Hybrids are made by crossing A-lines to R-lines that restore fertility in the A-lines due to the presence of restorer genes in their nuclei. R-lines and B-lines are found existing in nature. Good B-lines are converted to A-lines using a backcross method to any source of sterile cytoplasm (A1 cytoplasm being the most commonly used and stable sterile cytoplasm) with the B-line as the recurrent parent. The best R-lines are the ones with good general combining ability.

This system has been in use for 50 years until a recent molecular marker-based diversity study that utilized more detailed analysis indicated the existence of a more complex system of genetic relationships among elite parental lines (Menz et al., 2004). In this study, B and R lines did not show a consistent genetic dissimilarity characteristic of heterotic groups, and the groups observed through cluster analysis were somewhat in accordance with the phenotypic working group system (Murty and Govil, 1967; Harlan and deWet, 1972; Dahlberg, 2000). Five broadly-defined groups, and a sixth unrelated group, were observed. The groups have been designated as: Kafir-Milo derivative males, Kafir type females, Zerazera derivative males, Zerazera derivative females and Feterita derivative males.

# CHAPTER III

# MATERIALS AND METHODS

## Hybrid development

Twenty-six lines developed and tested for adaptation to Southern Africa were selected for testcross evaluation (Table 1). The 26 male testers are of diverse origin: two were developed by TAES for the U.S. sorghum industry, 14 are from the TAES sorghum improvement program and result from the introgression of African germplasm with U.S. adapted germplasm, three are from Southern Africa, two are from Central America and five are introductions from ICRISAT. The 26 male testers are all adapted to the tropical climate that is predominant in the Southern Africa region and all were selected based on desirable adaptation in Southern Africa regional tests. All of the males restore fertility to the A1 cytoplasm.

Each of the R-lines was test crossed to two standard U.S. female lines, ATx635 and ATx631. Both A-lines possess A1 cytoplasm.

ATx635 was released in 1992 in collaboration with ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) and the Texas Agriculture Experiment Station (TAES) (Miller et al., 1992). The line is nonsenescent, tan plant, straw glumes, white to translucent seed color, and short 2-dwarf ($dw_1Dw_2Dw_3dw_4$) height. It produces taller hybrids that are suitable for the Southern African region. ATx635 is tropically adapted and is resistant to head smut caused by *Sporisorium reiliana* (Kuehn) Lang. and Fullerton, and anthracnose caused by *Colletotrichum graminicola* (Ces.). ATx631 is one of the seven A and B lines that were released by TAES in 1985 (Miller et al., 1986). It is similar to ATx635 except that it is 3-dwarf ($dw_1Dw_2dw_3dw_4$) and susceptible to head smut caused by *Sporisorium reiliana* (Kuehn) Lang. and Fullerton. These two female lines possess good food quality characters, high yield potential and they transmit these traits to hybrids.

**Field evaluation**

The 52 hybrids, 28 parental lines and 4 checks were arranged in a randomized complete block design with three replications.

**Table 1.** Characteristics of all adapted parental lines that were used to evaluate heterosis at College Station, Weslaco, Halfway and Zambia in 2004.

| Parents | Seed color | Plant color | Comments |
|---|---|---|---|
| A.Tx635 | White | Tan | US female lines used to develop food grade hybrids. |
| A.Tx631 | White | Tan | |
| R.Tx436 | White | Tan | Lines popular in the US breeding programs to develop food grade hybrids. |
| R.Tx437 | White | Tan | |
| ((TAM428*SV1)*CE151)-LD3 | White | Tan | Lines developed in the Texas Agricultural Experimet Station Sorghum Breeding Program for adaptation to Southern Africa. |
| (Sureno*SRN39)-BE1 | White | Tan | |
| (Sureno*86EON362) | White | Tan | |
| (Macia*TAM428)-LL14 | White | Tan | |
| (87EON366*90EON328)-LD30 | White | Tan | |
| (WSV387*((CE151*BDM499)-LD17)) | White | Purple | |
| (87EON366*TAM428)-HF4 | White | Tan | |
| (87EON366*WSV387)-HD25 | White | Tan | |
| CE151-262-A1 | White | Tan | |
| ICSV-LM89510 | White | Tan | |
| (90EON328*(S35*ICSV401))-BE1 | Black | Purple | |
| (90EON328*CE151)-LD6 | White | Tan | |
| (LG70*ICSV400)-BE7 | White | Tan | |
| (M84-7*WSV387)-HD7 | White | Tan | |
| Tegemeo | White | Tan | Cultivars of Southern African origin that are currently grown as open pollinated varieties. |
| Macia | White | Tan | |
| Sureno | White | Tan | Cultivars of Central American origin. |
| Soberano | White | Purple | |
| Jocoro | White | Tan | |
| ICSV1089BF | White | Tan | ICRISAT lines from Mexico |
| ICSR-939 | White | Tan | |
| LM90538 | Red | Tan | |
| LM89537 | White | Tan | |
| LM90514 | White | Tan | |

The trial was grown in four environments: Golden Valley (Zambia), College Station (Texas), Weslaco (Texas) and Halfway (Texas). All locations had three replications except for Zambia in which only two replications were grown. The experimental unit was one row but varied in size with location: Halfway, 5.18 m x 1.02m; Weslaco, 3.96 m x 1.02 m; College Station 5.18 m x 0.76 m; and Zambia 4 m x 0.75 m. The experiments were grown using standard agronomic practices for the respective region, with supplemental irrigation to insure consistent and uniform yield expression (Table 2).

In all trials seed and plant color, days to mid-anthesis, plant height, exsertion, uniformity, desirability, lodging, panicle number and grain yield were measured. Plant height was measured as the height from the soil line to the tip of the panicle while panicle exsertion was measured from the base of the flag leaf to the base of the panicle. Plant color was either pigmented or tan and grain color was recorded as either white or red.

Uniformity of the plot was measured on a scale of 1 to 4 with 1 representing very uniform, 2 representing slight variation, 3 representing completely mixed and 4 representing significant genetic variation. Agronomic desirability was visually scored on a scale of 1 to 9 with 1 representing the most agronomically desirable line and 9 the least. Panicle number was counted prior to harvest and was used as a covariate to grain yield during analysis. Lodging was measured on a scale of 1 to 9 with 1 = 0% to 10% lodging, 2 = 11% to 20% lodging, 3 = 21% to 30% lodging up to 9 = 91% to 100% lodging.

All experiments were hand harvested on a plot by plot basis. 50 cm on both ends of each plot was discarded to avoid inter-plot competition effects. A bulk thresher was used to thresh harvested panicles on a plot by plot basis. Grain yield was measured in grams per plot adjusted to 12.5% moisture and later converted to tons/hectare using a conversion factor based on row width and plot length which differed across environments.

**Table 2.** Environmental data on Weslaco, College Station, Halfway (Texas) and Golden Valley (Zambia) in which the experiment was grown.

| Location | Soil Type | Altitude (m) | Latitude | Longitude | Plot length | Row spacing | Date Planted | Date Harvested | Fertilizer regime | Irrigations | Rainfall* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Weslaco (2004) | Raymondville clay loam | 22.5 | 26º09'N | 97º59'W | 18' | 40" | 02/12 | 07/02 | 1/21 50 gls/ha of 4-10-10 3/11 100lbs/ac as 32-0-0 3/26 100lbs/ac as 32-0-0 | None | 17.85" |
| College Station (2004) | Ships clay loam | 96.0 | 30º40'N | 96º21'W | 18' | 30" | 03/30 | 08/06 | 60-40-40 lbs/ac preplant, side-dressing of 60 lbs N/ac 05/05 | None | 26.4" |
| Halfway (2004) | Pullman clay loam | 1071.0 | 34º11'N | 101º57'W | 17' | 40" | 05/24 | 10/22 | 80+0+0 preplant | Two- 5/27 and 8/5 | 19.02" |
| Zambia (2004) | Clay Loam 2 | 1107.0 | 14º17'S | 28º27'E | 17' | 30'' | 12/12/03 | 05/19/04 | None | None | 22.59'' |

**Grain quality evaluation**

Quality analysis was completed on grain from the Halfway (Texas) environment because grain quality was not affected by grain mold weathering and was readily accessible for analysis. The following measurements were made:

1. Proximate analysis of starch, protein, oil and ash content were completed using Near-Infrared Reflectance Spectrophotometry. A wavelength scanning Dual Perten Instruments Model 7000 Near-Infrared Reflectance (NIR) Spectrophotometer was used to quantitatively determine the dry weight percentage of C-H (oils), N-H (protein) and O-H (water and carbohydrates). This analysis was carried out using whole grain samples in small ring cups. An average of three readings per sample was taken.
2. Kernel hardness was measured using the Single Kernel Hardness Tester (SKHT 4100 Perten Instruments, USA) on clean sound kernels of sorghum. This instrument measures hardness as the average amount of force required to crash 300 sound kernels within the sample. The force is recorded as a hardness index. Thus, the higher the index the harder the kernels. This instrument also records single kernel weight (mg) and diameter (mm). Data obtained from this instrument was not replicated. This data was used to conduct correlations only.
3. Decortication yields were measured using a tangential abrasive decorticator device (TADD Mill Model 4E-115) consisting of a twelve-cup dehulling plate used to measure grain hardness. Grain hardness was measured as percent weight removed by abrasive milling of kernels using an aluminum oxide abrasive disk. This method

measures the yield of decorticated grain. The higher the yield the harder the grain. Soft kernels lose more weight on milling because the loosely packed endosperm is more likely to break by abrasion. Two readings were taken per sample.

4. Visual determination of grain hardness: Visual determination of grain hardness according to the method of Rooney and Miller (1982) was used to measure grain hardness. This method relies on the relative proportion of the corneous to floury endosperm within a sorghum kernel i.e. endosperm texture. Texture is determined by visual examination of longitudinal half kernels. The scoring ranges from 1 to 5 with a rating of 1 meaning the kernel is almost completely corneous and 5 meaning the kernel is almost floury. The ratings of photos of unknown samples are compared with photos of standard samples that have been previously rated. Samples from the experiment were categorized as hard, intermediate and soft with Macia used as a check variety.
5. Color values: Hunter L*, a*, and b* values were obtained using a Minolta Chroma Meter DP-301 (colorimetric spectrophotometer) that uses the L*a*b* color space where L* indicates lightness of the sample (black is 0 and white is 100) and a* and b* are chromaticity coordinates. L* is the most important of the three and the analysis focused on Hunter L* values. An average of three readings was taken per sample.

**Statistical analysis**

Analysis of variance was done using PROC GLM procedure from SAS (SAS Institute Inc., 1997). Genotypes, including effects due to males, females, hybrids and parents were considered fixed effects while replications and environments were considered as random factors. Data analysis was completed on each environment before they were combined. Estimates of the general combining ability (GCA) of a male line was obtained in terms of its performance in $F_1$ hybrid combinations with all possible female lines. Likewise, the GCA of a female line was obtained in terms of its performance in $F_1$ hybrid combinations with all possible male lines. Specific combining ability (SCA) was obtained as deviation of individual crosses from the performance expected from the average of the parents. The formulas are as follows:

$GCA_A = A^* - Y^{**}$

$SCA_{A*B} = AB – (A^*+B^*)/2$

where

A*, B* = mean performance of line A and B, respectively.

Y** = grand mean.

AB = mean performance of the hybrid between lines A and B.

The mathematical model underlying the analysis of variance was as follows:

$$Y_{ijk} = \mu + f_i + m_j + (fm)_{ij} + r_k + (mr)_{jk} + (fr)_{ik} + e_{ijk}$$

where,

$Y_{ijk}$ = the observation on the hybrid between the $i^{th}$ female and the $j^{th}$ male in the $k^{th}$ replication of the experiment.

$\mu$ = the general mean.

$f_i$ = the effect of the $i^{th}$ female parent, $i$ = 1 to 2. Attributable to differences in general combining ability among female parents.

$m_j$ = the effect of the $j^{th}$ male parent, $j$ = 1 to 26. Attributable to differences in general combining ability among male parents.

$(fm)_{ij}$ = the interaction effect of the $i^{th}$ female and the $j^{th}$ male. Attributable to differences in specific combining ability.

$r_k$ = the effect of the $k^{th}$ replication, $k$ = 1 to 3.

$(mr)_{jk}$ = the interaction effect of the $j^{th}$ male and the $k^{th}$ replication.

$(fr)_{ik}$ = the interaction effect of the $i^{th}$ female and the $k^{th}$ replication.

$e_{ijk}$ = the effect of the subplot which had the hybrid between the $i^{th}$ female and the $j^{th}$ male in the $k^{th}$ replication of the experiment.

The forms of analysis of variances for cross-site analysis and single site analysis are shown on Tables 3 and 4 respectively. Genotype sums of squares were partitioned into parents, hybrids and parents vs. hybrids. The parents vs. hybrids contrast is an indicator of heterosis exhibited in an experiment. If this term is significant at the 0.05 and 0.01 level of significance in the analysis of variance then hybrids performed significantly better than their parents i.e. there is significant heterosis or otherwise.

Biplot analysis was used to explain the nature of the significant genotype by environment (G x E) interactions that were observed for grain yield and plant height.

These two traits were chosen because they are more heritable than exsertion and days to mid anthesis. Biplots were obtained using Microsoft Excel add-in Biplot software, with grain yield and plant height means of hybrids and parents in all four environments or locations. Biplots graphically illustrate the performance of all genotypes with respect to environmental conditions by grouping genotypes such that they fall in a sector toward the environment in which they performed best on average. Two principal components were used to explain G x E, the first explains most of the variation and the second explains lesser variation adding cumulatively to the total variation explained.

Analysis and interpretation of the biplot was done according to the methods reported by Yan and Hunt (2002). The four locations were joined by lines such that a quadrate was formed with all genotypes falling within the quadrate. The quadrate was then divided into sectors by lines drawn from the origin and perpendicular to the four sides of the quadrate. All genotypes that fall within a sector of the quadrate facing a particular environment performed well in that environment.

Pearson’s correlation coefficients were estimated for single kernel weight (skwt), kernel diameter (dia), test weight (twt), grain yield (yield), hardness measured using a TADD machine (TADD) and hardness measured using a single kernel hardness tester (hard) using the SPSS statistical software.

**Table 3.** Expected mean squares and appropriate F-tests for the combined analysis of variance across the four locations for all traits.

| Source | F Test | Expected Mean Square (EMS) |
|---|---|---|
| Env | $MS_E / MSe$ | $\sigma_e^2 + GRPHFM\sigma_E^2$ |
| Rep(Env) | $MS_{R(E)} / MSe$ | $\sigma_e^2 + GPHMF\sigma_{R(E)}^2$ |
| Genotype | $MS_G / MS_{GxE}$ | $\sigma_e^2 + RPHMF\sigma_{GxE}^2 + RPHMFE\sigma_G^2$ |
| Parents | $MS_P / MS_{PxE}$ | $\sigma_e^2 + GRHFM\sigma_{PxE}^2 + GRHFME\sigma_P^2$ |
| Females | $MS_F / MS_{FxE}$ | $\sigma_e^2 + +GRPHM\sigma_{FxE}^2 + GRPHME\sigma_F^2$ |
| Males | $MS_M / MS_{MxE}$ | $\sigma_e^2 + GRPHF\sigma_{MxE}^2 + GRPHFE\sigma_M^2$ |
| Females Vs Males | | |
| Hybrids | $MS_H / MS_{HxE}$ | $\sigma_e^2 + GRPFM\sigma_{HxE}^2 + GRPFME\sigma_H^2$ |
| Males | $MS_M / MS_{MxE}$ | $\sigma_e^2 + GRPHF\sigma_{MxE}^2 + GRPHFE\sigma_M^2$ |
| Females | $MS_F / MS_{FxE}$ | $\sigma_e^2 + GRPHM\sigma_{FxE}^2 + GRPHME\sigma_F^2$ |
| Female*Male | $MS_{FxM} / MS_e$ | $\sigma_e^2 + GRPHE\sigma_{FxM}^2$ |
| Parents Vs Hybrids | | |
| Gen*Env | $MS_{GxE} / MS_e$ | $\sigma_e^2 + RPHMF\sigma_{GxE}^2$ |
| Parents*Env | $MS_{PxE} / MS_e$ | $\sigma_e^2 + GRHFM\sigma_{PxE}^2$ |
| Males*Env | $MS_{MxE} / MS_e$ | $\sigma_e^2 + GRPHF\sigma_{MxE}^2$ |
| Females*Env | $MS_{FxE} / MS_e$ | $\sigma_e^2 + GRPHM\sigma_{FxE}^2$ |
| Hybrids*Env | $MS_{HxE} / MS_e$ | $\sigma_e^2 + GRPFM\sigma_{HxE}^2$ |
| Males*Env | $MS_{MxE} / MS_e$ | $\sigma_e^2 + GRPHF\sigma_{MxE}^2$ |
| Females*Env | $MS_{FxE} / MS_e$ | $\sigma_e^2 + GRPHM\sigma_{FxE}^2$ |
| Males*Fem*Env | $MS_{MxFxE} / MS_e$ | $\sigma_e^2 + GRPH\sigma_{MxFxE}^2$ |
| Error | | $\sigma_e^2$ |

**Table 4.** Expected mean squares and appropriate F-tests for single site analysis of variance for all traits.

| Source | F Test | Expected Mean Squares (EMS) |
|---|---|---|
| Rep | $MS_R / MS_e$ | $\sigma_e^2 + GHPMF\sigma_R^2$ |
| Genotype | $MS_G / MS_e$ | $\sigma_e^2 + RPMFH\sigma_G^2$ |
| Parents | $MS_P / MS_e$ | $\sigma_e^2 + GRHMF\sigma_P^2$ |
| Females | $MS_F / MS_e$ | $\sigma_e^2 + GRPHF\sigma_F^2$ |
| Males | $MS_M / MS_e$ | $\sigma_e^2 + GRPHF\sigma_M^2$ |
| Females Vs Males | | |
| Hybrids | $MS_H / MS_e$ | $\sigma_e^2 + GRPMF\sigma_H^2$ |
| Males | $MS_M / MS_e$ | $\sigma_e^2 + GRPHF\sigma_M^2$ |
| Females | $MS_F / MS_e$ | $\sigma_e^2 + GRPHF\sigma_F^2$ |
| Female*Male | $MS_{FxM} / MS_e$ | $\sigma_e^2 + GRPH\sigma_{MxF}^2$ |
| Parents Vs Hybrids | | |
| Error | | $\sigma_e^2$ |

# CHAPTER IV

# RESULTS AND DISCUSSION

## Zambia

Collaborators in Zambia did not record days to mid anthesis (DMA) and planted two replications instead of three (Table 5). In Zambia, genotypes were not significant for height and exsertion but were significant for yield. Overall the consistency of the data at this location was not good due in part to the minimal replication but also due to harvesting and threshing inconsistency from plot to plot. Heterosis was significant only for exsertion as seen in the significance levels for the Parents vs. Hybrids contrast.

**Table 5.** Mean squares for Ht (plant height in cm), Ex (panicle exsertion in cm) and Yield (grain yield in t/ha) for all eighty genotypes at Zambia in 2004.

| Source | DF | Yield † | Ex † | Ht † |
|---|---|---|---|---|
| Rep | 1 | 5.12$^{ns}$ | 21.76$^{ns}$ | 21.76$^{ns}$ |
| Genotype | 79 | 3.42* | 46.48$^{ns}$ | 1647.17$^{ns}$ |
| Parents | 27 | 2.92$^{ns}$ | 39.75* | 1734.31 $^{ns}$ |
| Females | 1 | 0.56$^{ns}$ | 2.25$^{ns}$ | 25$^{ns}$ |
| Males | 25 | 2.96$^{ns}$ | 37.25$^{ns}$ | 1737.48 $^{ns}$ |
| Females Vs | 1 | 4.29$^{ns}$ | 139.78* | 3364.32 $^{ns}$ |
| Hybrids | 51 | 3.64* | 41.21$^{ns}$ | 1596.96$^{ns}$ |
| Males | 25 | 3.33$^{ns}$ | 46.64$^{ns}$ | 1860.35$^{ns}$ |
| Females | 1 | 0.28$^{ns}$ | 3.85$^{ns}$ | 1218.62$^{ns}$ |
| Female*Male | 25 | 4.1* | 37.27$^{ns}$ | 1348.72$^{ns}$ |
| Parents Vs Hybrids | 1 | 5.18$^{ns}$ | 497.35** | 1855.0$^{ns}$ |
| Error | 79 | 2.15 | 34.16 | 1909.6 |
| | | | | |
| R-Square | - | 0.61 | 0.58 | 0.46 |
| CV (%) | - | 32.75 | 38.85 | 24.17 |
| Mean | - | 4.48 | 15.04 | 180.8 |

* ,** Significant at the 0.01, and 0.05 probability levels, respectively.

**Halfway**

Growth conditions in Halfway were generally good although there was too much rain. Significant effects were detected for all traits in at least one genotype category (Table 6). Data for plant height, exsertion and grain yield were consistent and reliable. Data for days to mid-anthesis (DMA) were suspect because they the range was limited to 73 to 76 days. This is a minimal range in flowering dates given the typical range seen in this germplasm (and in other locations within this study). Heterosis was highly significant for height, exsertion and yield as seen in the significance levels for the Parents vs. Hybrids contrast.

**Table 6.** Mean squares of DMA (days to mid anthesis), Ht (plant height in cm), Ex (panicle exsertion in cm) and Yield (grain yield in t/ha) for all eighty genotypes at Halfway in 2004.

| Source | DF | DMA† | Ht† | Ex† | DF | Yield† |
|---|---|---|---|---|---|---|
| Rep | 2 | $0.2^{ns}$ | $79.19^{ns}$ | $2.02^{ns}$ | 2 | 3.99* |
| Genotype | 79 | $1.08^{ns}$ | 1328.79** | 36.08** | 79 | 3.93** |
| Parents | 27 | $0.97^{ns}$ | 946.31** | 28.55** | 27 | 2.31** |
| Females | 1 | 1.5** | $38.5^{ns}$ | $17.2^{ns}$ | 1 | $0.08^{ns}$ |
| Males | 25 | $0.78^{ns}$ | 998.73** | 30.09** | 25 | 2.43** |
| Females Vs Males | 1 | $5.29^{ns}$ | 543.51* | 1.27ns | 1 | $1.19^{ns}$ |
| Hybrids | 51 | $1.16^{ns}$ | 839.76** | 30.72** | 51 | 3.76** |
| Males | 25 | $1.3^{ns}$ | 1381.18** | 38.28** | 25 | 4.78** |
| Females | 1 | $2.31^{ns}$ | 2248.84** | $9.31^{ns}$ | 1 | $1.75^{ns}$ |
| Female*Male | 25 | $0.98^{ns}$ | 241.97** | $24.01^{ns}$ | 25 | 2.77* |
| Parents Vs Hybrids | 1 | $0.001^{ns}$ | 36596.44** | 512.92** | 1 | 58.69** |
| Error | 158 | 1.21 | 70.11 | 12.60 | 153 | 1.20 |
| | | | | | | |
| R-Square | - | 0.31 | 0.90 | 0.59 | - | 0.63 |
| CV (%) | - | 1.47 | 5.11 | 47.48 | - | 31.5 |
| Mean | - | 75.08 | 163.99 | 7.48 | - | 3.48 |

* ,** Significant at the 0.01, and 0.05 probability levels, respectively.

**Weslaco**

Growth conditions in Weslaco were very good and management was excellent. The data was extremely consistent and differences due to genotypes were detected for all traits. A heterotic effect was detected for all traits as well as seen in the significance levels for the Parents vs. Hybrids contrast (Table 7). In this test, the R-square values were high and CVs were low. No variation was detected for DMA for females because both lines flowered on the same day (day 80).

**Table 7.** Mean squares of DMA (days to mid anthesis), Ht (plant height in cm), Ex (panicle exsertion in cm) and Yield (grain yield in t/ha) for all eighty genotypes at Weslaco in 2004.

| Source | DF | DMA† | Ex† | Ht† | DF | Yield† |
|---|---|---|---|---|---|---|
| Rep | 2 | 58** | 206.5** | 123.34* | 2 | 4.62** |
| Genotype | 79 | 26.59** | 80.25** | 1704.94** | 79 | 4.04** |
| Parents | 27 | 43.51** | 51.32** | 1182.37** | 27 | 3.52** |
| Females | 1 | $0^{ns}$ | $4.34^{ns}$ | 726* | 1 | 0.4* |
| Males | 25 | 46.9** | 55.2** | 1217.7** | 25 | 3.16** |
| Females Vs Males | 1 | $2.29^{ns}$ | $1.35^{ns}$ | 755.5** | 1 | 15.61** |
| Hybrids | 51 | 6.71* | 46.86** | 1057.52** | 51 | 4.07** |
| Males | 25 | 6.97* | 48.05** | 1767.14** | 25 | 4.83** |
| Females | 1 | 46.31** | 728.87** | 5420.92** | 1 | 15.34* |
| Female*Male | 25 | $4.86^{ns}$ | 18.37* | 173.36** | 25 | 2.86** |
| Parents Vs Hybrids | 1 | 583.88** | 2564.44** | 48832.98** | 1 | 16.22** |
| Error | 158 | 3.67 | 9.42 | 32.98 | 154 | 0.81 |
| | | | | | | |
| R-Square | - | 0.79 | 0.82 | 0.96 | - | 0.72 |
| CV | - | 2.48 | 26.43 | 3.67 | - | 21.64 |
| Mean | - | 77.28 | 11.61 | 156.39 | - | 4.17 |

* ,** Significant at the 0.01, and 0.05 probability levels, respectively.

**College Station**

There was too much rain at College Station leading to delays in planting and excessive tillering. The tillers where damaged by midge and this affected the yield potential of some entries and contributed to high C.V. for yield (Table 8). Midge damage or incidence was not measured to be used as a covariate. Significant effects due to genotypes were detected for all four traits and the consistency of the data was relatively good. Heterosis was detected for all four traits as well as seen in the significance levels for the Parents vs. Hybrids contrast.

**Table 8.** Mean squares of DMA (days to mid anthesis), Ht (plant height in cm), Ex (panicle exsertion in cm) and Yield (grain yield in t/ha) for all eighty genotypes at College Station in 2004.

| Source | DF | DMA† | Ex† | Ht† | DF | Yield† |
|---|---|---|---|---|---|---|
| Rep | 2 | 242.096** | 27.92$^{ns}$ | 17456.31** | 2 | 11.24** |
| Genotype | 79 | 45.05** | 51.48** | 2222.36** | 79 | 0.72* |
| Parents | 27 | 59.27** | 41.81** | 2171.57** | 27 | 0.61* |
| Females | 1 | 13.5$^{ns}$ | 26.46$^{ns}$ | 26.88$^{ns}$ | 1 | 0.08$^{ns}$ |
| Males | 25 | 63.26** | 37.39** | 2318.44** | 25 | 0.62* |
| Females Vs Males | 1 | 12.67$^{ns}$ | 167.26** | 658.69$^{ns}$ | 1 | 0.74$^{ns}$ |
| Hybrids | 51 | 27.63$^{ns}$ | 23.19* | 1047.75** | 51 | 0.48$^{ns}$ |
| Males | 25 | 46.73** | 26.89* | 1881.62** | 25 | 0.44$^{ns}$ |
| Females | 1 | 10.77$^{ns}$ | 16.28$^{ns}$ | 1043.67$^{ns}$ | 1 | 0.49$^{ns}$ |
| Female*Male | 25 | 9.2$^{ns}$ | 19.77* | 214.04* | 25 | 0.52$^{ns}$ |
| Parents Vs Hybrids | 1 | 516.32** | 1746.06** | 61073.54** | 1 | 15.66** |
| Error | 156 | 18.17 | 10.34 | 161.4 | 153 | 0.499 |
| | | | | | | |
| R-Square | - | 0.59 | 0.72 | 0.89 | - | 0.51 |
| CV (%) | - | 4.93 | 34.85 | 7.93 | - | 51.82 |
| Mean | - | 86.44 | 9.23 | 160.19 | - | 1.36 |

* ,** Significant at the 0.01, and 0.05 probability levels, respectively.

**Combined analysis**

Prior to combining the data from the four environments, Bartlett's test for homogeneity was conducted (Steel and Torrie, 1980). The test indicated that the error terms were normally distributed and the data can be combined for further analysis.

Significant variation was detected among genotypes for all four traits (Table 9). Differences were also found among parent lines for all traits. This variation was due to the male parents as differences were not detected among female parents for any trait. In the hybrids significant effects were detected for all traits except for females and the female*male interaction for DMA. The lack of significance for this trait was likely caused by the minimal variation recorded in the Halfway location.

Heterosis was highly significant for all four traits in the combined analysis as shown by the contrast between parents and hybrids (Table 9). Each trait exhibited its own unique level of heterosis. Heterosis for grain yield averaged 37.18% ranging from 113.52% for ATx631/ ((TAM428*SV1)*CE151)-LD3 to -28.37% for ATx635/((TAM428*SV1)*CE151)-LD3. Heterosis for exsertion averaged 82.77% ranging from 99.94% for ATx631/(LG70*ICSV400)-BE7 to -34.66% for ATx631/((TAM428*SV1)*CE151)-LD3. Heterosis for plant height averaged 23.7% ranging from 70.39% for ATx631/(87EON366*90EON328)-LD30 to -28.31% for ATx631/Sureno. Heterosis for days to mid-anthesis was negative averaging –0.02% ranging from 28.6% for ATx631/(M84-7*WSV387)-HD7 to -6.53% for ATx631/Tegemeo. A negative heterosis for days to mid anthesis means that hybrids matured earlier than their parents on average.

The highest yielding genotype was [A/BTx631/(87EON366*90EON328)-LD30] at 5.04t/ha and the lowest was [A/BTx635/((TAM428*SV1)*CE151)-LD3] at 1.44 t/ha (Table 10). Most hybrids were in the top forty of the eighty genotypes when ranked on yield and parents were in the bottom half. This shows that hybrids generally yielded higher than their parents as expected. The top two highest yielding genotypes A/BTx631/(87EON366*90EON328)-LD30 and A/BTx631/((TAM428*SV1)*CE151)-LD3 yielded 5.04t/ha and 4.93 t/ha respectively. Check varieties Macia and Tegemeo yielded 2.21 t/ha and 2.18 t/ha respectively. This doubling in yield clearly indicates the superiority of hybrids over open pollinated varieties.

Constant-parent heterosis is defined as an average heterosis for one parent across different crosses. There were twelve hybrids with ATx631 as their female parent in the top 20 genotypes. ATx631 had a constant-parent heterosis of 41.03% for yield and its hybrids averaged 3.85 t/ha compared to ATx635 that had a constant-parent heterosis of 35.22% and its hybrids averaged 3.60 t/ha (Tables 10 and 11 respectively). This means that ATx631 is a better parent than ATx635 for yield for the male pollinators included in this study.

**Table 9.** Mean squares of the combined analysis of variance of DMA (days to mid anthesis), Ht (plant height in cm), Ex (panicle exsertion in cm) and Yield (grain yield in t/ha) for all eighty genotypes at College Station, Weslaco, Halfway, Texas and Golden Valley, Zambia in 2004.

| Source | DF | Yield | DF | Ht | DF | Ex | DF | DMA |
|---|---|---|---|---|---|---|---|---|
| Env | 3 | 434.58** | 3 | 22524.5** | 3 | 2094.57** | 2 | 8686.53** |
| Rep(Env) | 7 | 6.38** | 7 | 4968.0** | 7 | 70.42** | 6 | 98.37** |
| Genotype | 79 | 6.62** | 79 | 7377.03** | 79 | 162.37** | 79 | 38.03** |
| Parents | 27 | 2.49** | 27 | 4620.63** | 27 | 112.64** | 27 | 53.05** |
| Females | 1 | $0.49^{ns}$ | 1 | $316.92^{ns}$ | 1 | $2.58^{ns}$ | 1 | $2.0^{ns}$ |
| Males | 25 | 2.37** | 25 | 4919.41** | 25 | 117.87** | 25 | 57.17** |
| Females Vs Males | 1 | 7.26** | 1 | 1459.46** | 1 | 87.53* | 1 | $2.11^{ns}$ |
| Hybrids | 51 | 5.03** | 51 | 4474.96** | 51 | 60.18** | 51 | 16.02** |
| Males | 25 | 5.98** | 25 | 7842.19** | 25 | 85.97** | 25 | 26.32** |
| Females | 1 | 20.75** | 1 | 12890.55** | 1 | 166.39* | 1 | $24.46^{ns}$ |
| Female*Male | 25 | 3.44** | 25 | 771.01** | 25 | 30.15* | 25 | $5.38^{ns}$ |
| Parents Vs Hybrids | 1 | 199.36** | 1 | 228847.73** | 1 | 6754.84** | 1 | 752.23** |
| Gen*Env | 237 | 2.06** | 237 | 320.57** | 237 | 23.45** | 158 | 17.35** |
| Parents*Env | 81 | 1.95** | 81 | 301.75** | 81 | 20.11** | 54 | 25.35** |
| Males*Env | 75 | 1.96** | 75 | 311.3** | 75 | 19.88** | 50 | 26.89** |
| Females*Env | 3 | $0.03^{ns}$ | 3 | $191.49^{ns}$ | 3 | $15.14^{ns}$ | 2 | $6.5^{ns}$ |
| Hybrids*Env | 153 | 1.61** | 153 | 233.79** | 153 | 21.15** | 102 | $9.74^{ns}$ |
| Males*Env | 75 | 1.96** | 75 | 339.03** | 75 | 17.897* | 50 | 14.34* |
| Females*Env | 3 | 2.72* | 3 | 658.91** | 3 | 201.41** | 2 | $17.47^{ns}$ |
| Males*Fem*Env | 75 | $1.19^{ns}$ | 75 | 111.54** | 75 | 17.198* | 50 | $4.83^{ns}$ |
| Error | 775 | 1.22 | 789 | 156.1 | 787 | 15.03 | 630 | 10.07 |
| R-Square | - | 0.66 | - | 0.85 | - | 0.62 | - | 0.77 |
| CV(%) | - | 33.6 | - | 7.61 | - | 37.06 | - | 3.99 |
| Mean | - | 3.28 | - | 164.13 | - | 10.46 | - | 79.58 |

* ,** Significant at the 0.01, and 0.05 probability levels, respectively.

**Table 10.** Means for Yield (grain yield in t/ha), Ex (panicle exsertion in cm), Ht (plant height in cm) and DMA (days to mid anthesis) for all eighty genotypes across all four environments in 2004.

| **Pedigree** | **Gen§** | **Rank** | **Yield** | **Ex** | **Ht** | **DMA** |
|---|---|---|---|---|---|---|
| ATx631/(87EON366*90EON328)-LD30 | 61 | 1 | 5.04 | 8.96 | 224.86 | 80.67 |
| ATx631/((TAM428*SV1)*CE151)-LD3 | 57 | 2 | 4.93 | 6.95 | 229.47 | 80.33 |
| ATx631/ICSR-939 | 77 | 3 | 4.66 | 13.59 | 198.68 | 80.78 |
| ATx635/(87EON366*WSV387)-HD25 | 38 | 4 | 4.63 | 10.64 | 175.51 | 78.33 |
| ATx631/LM89537 | 79 | 5 | 4.61 | 12.75 | 188.60 | 80.00 |
| ATx631/(90EON328*(S35*ICSV401))-BE1 | 67 | 6 | 4.60 | 15.57 | 190.17 | 80.22 |
| ATx635/ICSR-939 | 51 | 7 | 4.56 | 13.49 | 203.96 | 80.22 |
| ATx635/(Macia*TAM428)-LL14 | 52 | 8 | 4.33 | 11.78 | 176.87 | 78.00 |
| ATx631/(Sureno*86EON362) | 58 | 9 | 4.33 | 10.27 | 222.11 | 80.44 |
| ATx635/(87EON366*TAM428)-HF4 | 37 | 10 | 4.28 | 11.45 | 194.30 | 79.89 |
| ATx631/(LG70*ICSV400)-BE7 | 73 | 11 | 4.26 | 18.60 | 198.00 | 80.22 |
| ATx631/Jocoro | 75 | 12 | 4.21 | 9.66 | 188.79 | 79.89 |
| ATx631/CE151-262-A1 | 65 | 13 | 4.19 | 10.55 | 178.90 | 79.56 |
| ATx631/Macia | 70 | 14 | 4.16 | 13.72 | 178.44 | 79.89 |
| ATx631/ICSV1089BF | 69 | 15 | 4.12 | 12.50 | 192.67 | 79.22 |
| ATx635/Soberano | 50 | 16 | 4.10 | 11.34 | 163.52 | 76.78 |
| ATx635/(WSV387*((CE151*BDM499)-LD17)) | 36 | 17 | 4.07 | 14.96 | 163.07 | 77.67 |
| ATx635/(87EON366*90EON328)-LD30 | 35 | 18 | 4.04 | 12.56 | 169.70 | 76.78 |
| ATx635/(90EON328*(S35*ICSV401))-BE1 | 41 | 19 | 4.01 | 13.15 | 186.29 | 80.33 |
| ATx631/(87EON366*TAM428)-HF4 | 63 | 20 | 3.99 | 12.38 | 192.24 | 79.00 |
| ATx635/CE151-262-A1 | 39 | 21 | 3.98 | 14.32 | 187.23 | 79.22 |
| ATx635/(90EON328*CE151)-LD6 | 42 | 22 | 3.95 | 14.24 | 168.36 | 79.33 |
| ATx635/ICSV1089BF | 43 | 23 | 3.95 | 15.18 | 183.07 | 79.67 |
| ATX631*RTX437 | 56 | 24 | 3.95 | 11.78 | 167.20 | 78.44 |
| ATx635/Jocoro | 49 | 25 | 3.94 | 11.74 | 183.51 | 78.00 |
| ATx631/(M84-7*WSV387)-HD7 | 74 | 26 | 3.87 | 17.16 | 179.14 | 79.44 |
| ATX635*RTx437 | 30 | 27 | 3.86 | 15.93 | 156.15 | 77.33 |
| ATX631*RTx436 | 55 | 28 | 3.83 | 11.89 | 170.07 | 78.33 |

**Table 10.** Continued.

| Pedigree | Gen§ | Rank | Yield | Ex | Ht | DMA |
|---|---|---|---|---|---|---|
| ICSV1089BF | 17 | 29 | 3.79 | 5.94 | 186.77 | 81.11 |
| ATx635/LM89537 | 53 | 30 | 3.65 | 13.12 | 175.48 | 76.56 |
| ATx631/LM90538 | 59 | 31 | 3.60 | 13.27 | 198.95 | 79.67 |
| ATX635*RTx436 | 29 | 32 | 3.54 | 15.56 | 151.77 | 77.00 |
| LM90538 | 7 | 33 | 3.49 | 5.79 | 156.65 | 81.89 |
| ATx635/LM90514 | 54 | 34 | 3.44 | 14.55 | 172.67 | 79.00 |
| ATx635/(M84-7*WSV387)-HD7 | 48 | 35 | 3.43 | 13.46 | 160.77 | 76.11 |
| ATx631/ICSV-LM89510 | 66 | 36 | 3.41 | 9.95 | 165.59 | 79.22 |
| ATx631/Soberano | 76 | 37 | 3.41 | 12.21 | 175.47 | 80.67 |
| ATx635/(LG70*ICSV400)-BE7 | 47 | 38 | 3.37 | 14.51 | 162.57 | 77.67 |
| ATx631/LM90514 | 80 | 39 | 3.36 | 13.03 | 173.40 | 78.56 |
| ATx635/Macia | 44 | 40 | 3.34 | 14.04 | 165.12 | 78.33 |
| ATx635/LM90538 | 33 | 41 | 3.31 | 9.57 | 156.13 | 79.33 |
| CE151-262-A1 | 13 | 42 | 3.28 | 5.49 | 133.86 | 78.00 |
| LM90514 | 28 | 43 | 3.28 | 3.51 | 126.51 | 81.00 |
| ATx631/(Sureno*SRN39)-BE1 | 60 | 44 | 3.28 | 14.36 | 181.91 | 79.00 |
| ATx631/(90EON328*CE151)-LD6 | 68 | 45 | 3.28 | 12.80 | 174.55 | 78.89 |
| ATx631/(Macia*TAM428)-LL14 | 78 | 46 | 3.26 | 13.03 | 176.87 | 79.89 |
| ICSV-LM89510 | 14 | 47 | 3.24 | 6.55 | 173.88 | 82.67 |
| ATx631/(87EON366*WSV387)-HD25 | 64 | 48 | 3.21 | 12.81 | 176.16 | 78.44 |
| (M84-7*WSV387)-HD7 | 22 | 49 | 3.19 | 7.60 | 157.58 | 61.78 |
| ATx635/Tegemeo | 46 | 50 | 3.11 | 12.26 | 150.61 | 78.11 |
| ATx635/(Sureno*86EON362) | 32 | 51 | 3.10 | 14.36 | 157.56 | 76.33 |
| ATx631/Tegemeo | 72 | 52 | 3.10 | 15.06 | 160.30 | 76.33 |
| R.TX437 | 4 | 53 | 3.05 | 10.56 | 114.50 | 75.56 |
| (87EON366*90EON328)-LD30 | 9 | 54 | 3.05 | 1.57 | 124.89 | 80.00 |
| (WSV387*((CE151*BDM499)-LD17)) | 10 | 55 | 3.04 | 6.51 | 134.30 | 77.00 |
| ATx635/Sureno | 45 | 56 | 2.93 | 7.78 | 142.57 | 79.11 |
| Jocoro | 23 | 57 | 2.90 | 5.69 | 163.97 | 83.78 |
| Soberano | 24 | 58 | 2.90 | 6.42 | 113.59 | 76.89 |
| ATx635/(Sureno*SRN39)-BE1 | 34 | 59 | 2.90 | 13.49 | 161.43 | 80.00 |
| (Macia*TAM428)-LL14 | 26 | 60 | 2.80 | 2.54 | 127.84 | 81.00 |

**Table 10.** Continued.

| Pedigree | Gen§ | Rank | Yield | Ex | Ht | DMA |
|---|---|---|---|---|---|---|
| (90EON328*CE151)-LD6 | 16 | 61 | 2.77 | 1.33 | 138.22 | 83.78 |
| (Sureno*SRN39)-BE1 | 8 | 62 | 2.75 | 7.47 | 128.80 | 80.33 |
| ICSR-939 | 25 | 63 | 2.75 | 13.82 | 158.01 | 83.78 |
| ATx631/Sureno | 71 | 64 | 2.73 | 8.39 | 135.23 | 78.78 |
| ATx631/(WSV387*((CE151*BDM499)-LD17)) | 62 | 65 | 2.69 | 14.82 | 220.96 | 80.78 |
| (Sureno*86EON362) | 6 | 66 | 2.67 | 7.15 | 122.36 | 78.89 |
| (90EON328*(S35*ICSV401))-BE1 | 15 | 67 | 2.64 | 6.76 | 138.46 | 78.45 |
| (LG70*ICSV400)-BE7 | 21 | 68 | 2.41 | 9.02 | 164.48 | 83.74 |
| (87EON366*WSV387)-HD25 | 12 | 69 | 2.39 | 9.17 | 123.71 | 80.56 |
| ATx635/ICSV-LM89510 | 40 | 70 | 2.39 | 16.63 | 166.75 | 78.89 |
| LM89537 | 27 | 71 | 2.34 | 5.19 | 160.27 | 84.11 |
| B.Tx631 | 2 | 72 | 2.31 | 9.30 | 131.97 | 81.67 |
| Sureno | 19 | 73 | 2.30 | 9.90 | 188.63 | 83.00 |
| (87EON366*TAM428)-HF4 | 11 | 74 | 2.22 | 5.73 | 127.79 | 83.11 |
| Macia | 18 | 75 | 2.21 | 8.67 | 152.93 | 81.44 |
| R.Tx436 | 3 | 76 | 2.19 | 14.45 | 126.70 | 77.33 |
| Tegemeo | 20 | 77 | 2.18 | 4.82 | 156.83 | 83.89 |
| B.Tx635 | 1 | 78 | 2.01 | 8.62 | 139.56 | 81.00 |
| ((TAM428*SV1)*CE151)-LD3 | 5 | 79 | 1.90 | 10.64 | 143.76 | 82.11 |
| ATx635/((TAM428*SV1)*CE151)-LD3 | 31 | 80 | 1.44 | 13.13 | 154.07 | 75.89 |
| **Overall mean** | - | - | 3.27 | 10.46 | 164.13 | 79.58 |
| **Mean ATx635 hybrids** | - | - | 3.60 | 13.20 | 168.81 | 78.23 |
| **Mean ATx631 hybrids** | - | - | 3.85 | 12.54 | 186.11 | 79.48 |
| **Mean of parents** | - | - | 2.72 | 7.04 | 143.46 | 80.28 |
| **Mean of hybrids** | - | - | 3.73 | 12.87 | 177.46 | 78.85 |
| **Heterosis (Parents vs Hybrids) (%)** | - | - | 37.18 | 82.77 | 23.70 | -0.02 |
| **LSD (0.05)** | - | - | 0.932 | 3.256 | 10.476 | 2.943 |

§ Genotype number.

**Table 11.** High parent heterosis expressed for grain yield (Yield), panicle exsertion (Ex), plant height (Ht) and negative heterosis for days to mid anthesis (DMA) among the fifty-two hybrids ranked according to high parent heterosis for yield.

| Pedigree | Rank | Yield % | Ex % | Ht % | DMA % |
|---|---|---|---|---|---|
| ATx631/((TAM428*SV1)*CE151)-LD3 | 1 | 113.52 | -34.66 | 59.63 | -1.63 |
| ATx631/LM89537 | 2 | 97.25 | 37.07 | 17.67 | -2.04 |
| ATx635/(87EON366*WSV387)-HD25 | 3 | 93.31 | 16.10 | 25.76 | -2.76 |
| ATx635/(87EON366*TAM428)-HF4 | 4 | 92.90 | 32.91 | 39.23 | -1.37 |
| ATX635*RTx437 | 5 | 91.73 | 50.84 | 11.89 | 2.35 |
| ATx631/Macia | 6 | 79.97 | 47.45 | 16.68 | -2.18 |
| ATx631/(LG70*ICSV400)-BE7 | 7 | 76.91 | 99.94 | 20.38 | -1.77 |
| ATx631/(90EON328*(S35*ICSV401))-BE1 | 8 | 74.12 | 67.32 | 37.35 | 1.97 |
| ATx631/(87EON366*TAM428)-HF4 | 9 | 72.65 | 33.06 | 45.67 | -3.27 |
| ATx631/ICSR-939 | 10 | 69.63 | -1.64 | 25.74 | -1.09 |
| ATx635/ICSR-939 | 11 | 66.02 | -2.33 | 29.08 | -0.96 |
| ATx631*RTx436 | 12 | 65.70 | 27.77 | 28.88 | 1.29 |
| ATx631/(87EON366*90EON328)-LD30 | 13 | 65.15 | -3.73 | 70.39 | 0.83 |
| ATx631/(Sureno*86EON362) | 14 | 62.11 | 10.38 | 68.31 | 1.97 |
| ATx635*RTx436 | 15 | 61.88 | 7.63 | 8.76 | -0.43 |
| ATx635/LM89537 | 16 | 56.19 | 52.19 | 9.49 | -5.49 |
| ATx635/(Macia*TAM428)-LL14 | 17 | 54.5 | 36.71 | 26.73 | -3.70 |
| ATx635/(90EON328*(S35*ICSV401))-BE1 | 18 | 51.71 | 52.59 | 33.49 | 2.40 |
| ATx635/Macia | 19 | 51.39 | 61.91 | 7.97 | -3.29 |
| ATx631/Jocoro | 20 | 45.15 | 3.83 | 15.14 | -2.18 |
| ATx635/(90EON328*CE151)-LD6 | 21 | 42.88 | 65.21 | 20.64 | -2.06 |
| ATx635/Tegemeo | 22 | 42.61 | 42.28 | -3.96 | -3.57 |
| ATx635/Soberano | 23 | 41.48 | 31.56 | 17.17 | -0.14 |
| ATx635/(LG70*ICSV400)-BE7 | 24 | 39.95 | 60.85 | -1.16 | -4.12 |
| ATx635/Jocoro | 25 | 36.06 | 36.26 | 11.91 | -3.70 |
| ATx631/Tegemeo | 26 | 34.26 | 61.85 | 2.21 | -6.53 |
| ATx631/(87EON366*WSV387)-HD25 | 27 | 34.20 | 37.72 | 33.49 | -2.62 |
| ATx635/(WSV387*((CE151*BDM499)-LD17)) | 28 | 33.79 | 73.62 | 16.85 | 0.87 |
| ATx635/(87EON366*90EON328)-LD30 | 29 | 32.37 | 45.71 | 21.60 | -4.03 |
| ATx631*RTX437 | 30 | 29.63 | 11.59 | 26.70 | 3.82 |
| ATx631/CE151-262-A1 | 31 | 27.56 | 13.37 | 33.65 | 1.99 |
| ATx635/Sureno | 32 | 27.43 | -21.40 | -24.42 | -2.33 |
| ATx631/(M84-7*WSV387)-HD7 | 33 | 21.29 | 84.40 | 13.68 | 28.60 |
| ATx635/CE151-262-A1 | 34 | 21.22 | 66.20 | 39.87 | 1.57 |
| ATx631/(Sureno*SRN39)-BE1 | 35 | 19.28 | 54.33 | 41.23 | -1.66 |
| ATx631/(90EON328*CE151)-LD6 | 36 | 18.47 | 37.58 | 26.28 | -3.40 |
| ATx631/Sureno | 37 | 18.33 | -15.23 | -28.31 | -3.54 |

**Table 11.** Continued.

| Pedigree | Rank | Yield % | Ex % | Ht % | DMA % |
|---|---|---|---|---|---|
| ATx631/Soberano | 38 | 17.60 | 31.19 | 54.47 | 4.91 |
| ATx635/(Sureno*86EON362) | 39 | 16.27 | 66.62 | 12.90 | -3.24 |
| ATx631/(Macia*TAM428)-LL14 | 40 | 16.21 | 40.00 | 34.02 | -1.37 |
| ATx631/ICSV1089BF | 41 | 8.61 | 34.39 | 3.16 | -2.99 |
| ATx635/(M84-7*WSV387)-HD7 | 42 | 7.29 | 56.18 | 2.02 | 23.20 |
| ATx635/(Sureno*SRN39)-BE1 | 43 | 5.48 | 56.47 | 15.67 | -0.41 |
| ATx631/ICSV-LM89510 | 44 | 5.02 | 6.98 | -4.77 | -2.99 |
| ATx635/LM90514 | 45 | 4.99 | 68.88 | 23.73 | -2.47 |
| ATx635/ICSV1089BF | 46 | 4.34 | 76.18 | -1.99 | -1.65 |
| ATx631/LM90538 | 47 | 3.23 | 42.60 | 27.00 | -2.45 |
| ATx631/LM90514 | 48 | 2.44 | 40.08 | 31.4 | -3.02 |
| ATx635/LM90538 | 49 | -5.31 | 11.05 | -0.33 | -2.06 |
| ATx631/(WSV387*((CE151*BDM499)-LD17)) | 50 | -11.56 | 59.31 | 64.52 | 4.91 |
| ATx635/ICSV-LM89510 | 51 | -26.29 | 92.95 | -4.10 | -2.61 |
| ATx635/((TAM428*SV1)*CE151)-LD3 | 52 | -28.37 | 23.45 | 7.18 | -6.31 |
| ATx631 CPH‡ | - | 41.03 | 31.80 | 29.41 | 0.21 |
| ATx635 CPHΨ | - | 35.22 | 44.64 | 13.31 | -1.01 |

‡ Constant parent heterosis for ATx631.
Ψ Constant parent heterosis for ATx635.

**Table 12.** Ranking of general combining abilities for all 26 male parents testcrossed to ATx631 and ATx635 for Yield (yield in t/ha), Ex (panicle exsertion in cm), Ht (plant height in cm), and DMA (days to mid anthesis) tested at College Station, Zambia, Weslaco and Halfway in 2004.

| Pedigree | Yield | Ex | Ht | DMA |
|---|---|---|---|---|
| ICSR-939 | 0.88 | 0.67 | 23.86 | 1.65 |
| (87EON366*90EON328)-LD30 | 0.81 | -2.11 | 19.82 | -0.13 |
| (90EON328*(S35*ICSV401))-BE1 | 0.58 | 1.49 | 10.78 | 1.31 |
| (87EON366*TAM428)-HF4 | 0.41 | -0.95 | 15.81 | 0.59 |
| LM89537 | 0.41 | 0.06 | 4.59 | -0.57 |
| CE151-262-A1 | 0.36 | -0.44 | 5.61 | 0.54 |
| Jocoro | 0.35 | -2.17 | 8.69 | 0.09 |
| ICSV1089BF | 0.31 | 0.97 | 10.41 | 0.59 |
| (87EON366*WSV387)-HD25 | 0.20 | -1.14 | -1.62 | -0.46 |
| R.TX437 | 0.18 | 0.99 | -15.78 | -0.96 |
| (LG70*ICSV400)-BE7 | 0.09 | 3.68 | 2.83 | 0.09 |
| (Macia*TAM428)-LL14 | 0.07 | -0.47 | -0.59 | 0.09 |
| Soberano | 0.03 | -1.10 | -7.96 | -0.13 |
| Macia | 0.02 | 1.01 | -5.68 | 0.26 |
| (Sureno*86EON362) | -0.01 | -0.56 | 12.38 | -0.46 |
| R.Tx436 | -0.04 | 0.85 | -16.53 | -1.19 |
| (M84-7*WSV387)-HD7 | -0.08 | 2.44 | -7.50 | -1.07 |
| (90EON328*CE151)-LD6 | -0.11 | 0.65 | -6.01 | 0.26 |
| LM90538 | -0.27 | -1.45 | 0.08 | 0.65 |
| LM90514 | -0.33 | 0.92 | -4.42 | -0.07 |
| (WSV387*((CE151*BDM499)-LD17)) | -0.34 | 2.02 | 14.55 | 0.37 |
| ((TAM428*SV1)*CE151)-LD3 | -0.54 | -2.83 | 14.32 | -0.74 |
| Tegemeo | -0.62 | 0.79 | -22.00 | -1.63 |
| (Sureno*SRN39)-BE1 | -0.63 | 1.05 | -5.79 | 0.65 |
| ICSV-LM89510 | -0.83 | 0.42 | -11.29 | 0.20 |
| Sureno | -0.90 | -4.79 | -38.56 | 0.09 |

**Table 13.** Specific combining abilities for all the 26 male parents testcrossed to ATx631 and ATx635 for Yield (yield in t/ha), Ex (panicle exsertion in cm), Ht (plant height in cm), and DMA (days to mid anthesis) tested at College Station, Zambia, Weslaco and Halfway in 2004.

| | Yield | | Ex | | Ht | | DMA | |
|---|---|---|---|---|---|---|---|---|
| **Pedigree** | **ATx635** | **ATx631** | **ATx635** | **ATx631** | **ATx635** | **ATx631** | **ATx635** | **ATx631** |
| R.Tx436 | -0.10 | 0.06 | 2.10 | -1.24 | -13.09 | -3.44 | -0.95 | -0.24 |
| R.TX437 | 0.10 | 0.07 | 2.40 | -1.41 | -9.09 | -6.69 | -0.72 | -0.24 |
| ((TAM428*SV1)*CE151)-LD3 | -1.95 | 1.42 | 1.51 | -4.34 | -26.22 | 40.53 | -2.28 | 1.54 |
| (Sureno*86EON362) | -0.56 | 0.54 | 1.60 | -2.16 | -21.77 | 34.14 | -1.97 | 1.51 |
| LM90538 | -0.22 | -0.05 | -2.74 | 1.29 | -17.04 | 17.13 | 0.47 | 0.18 |
| (Sureno*SRN39)-BE1 | -0.44 | -0.19 | -0.08 | 1.13 | -8.81 | 3.02 | 1.14 | -0.49 |
| (87EON366*90EON328)-LD30 | -0.03 | 0.84 | 0.58 | -2.69 | -13.34 | 33.16 | -1.70 | 1.57 |
| (WSV387*((CE151*BDM499)-LD17)) | 0.58 | -0.92 | 0.92 | 1.11 | -17.34 | 31.90 | -1.06 | 1.43 |
| (87EON366*TAM428)-HF4 | 0.41 | 0.00 | -1.11 | 0.15 | 13.26 | 2.55 | 1.05 | -0.46 |
| (87EON366*WSV387)-HD25 | 0.87 | -0.67 | -1.82 | 0.68 | 3.19 | -4.81 | 0.03 | -0.49 |
| CE151-262-A1 | 0.14 | 0.22 | 1.50 | -1.94 | 11.29 | -5.68 | 0.41 | 0.12 |
| ICSV-LM89510 | -0.86 | 0.03 | 3.38 | -2.96 | -0.74 | -10.54 | 0.25 | -0.04 |
| (90EON328*(S35*ICSV401))-BE1 | 0.06 | 0.53 | -0.63 | 2.12 | 7.77 | 3.01 | 1.14 | 0.18 |
| (90EON328*CE151)-LD6 | 0.34 | -0.45 | 0.88 | -0.23 | -1.77 | -4.23 | 0.66 | -0.41 |
| ICSV1089BF | 0.14 | 0.17 | 1.66 | -0.69 | 4.73 | 5.69 | 0.83 | -0.24 |
| Macia | -0.33 | 0.36 | 0.50 | 0.51 | -5.17 | -0.50 | -0.34 | 0.59 |
| Sureno | -0.29 | -0.61 | -2.86 | -1.92 | -11.28 | -27.27 | 0.53 | -0.43 |
| Tegemeo | -0.25 | -0.37 | -1.17 | 1.96 | -11.52 | -10.48 | 0.39 | -2.02 |
| (LG70*ICSV400)-BE7 | -0.34 | 0.43 | -0.37 | 4.05 | -11.97 | 14.81 | -0.92 | 1.01 |
| (M84-7*WSV387)-HD7 | -0.20 | 0.12 | -0.80 | 3.23 | -8.61 | 1.11 | -1.89 | 0.82 |
| Jocoro | 0.11 | 0.25 | -0.21 | -1.96 | 6.03 | 2.66 | -0.59 | 0.68 |
| Soberano | 0.42 | -0.39 | -1.15 | 0.05 | -5.63 | -2.33 | -1.70 | 1.57 |
| ICSR-939 | 0.45 | 0.43 | 0.12 | 0.55 | 18.89 | 4.97 | 0.86 | 0.79 |
| (Macia*TAM428)-LL14 | 0.63 | -0.56 | -1.02 | 0.55 | 4.03 | -4.62 | -0.59 | 0.68 |
| LM89537 | -0.22 | 0.62 | 0.05 | 0.02 | 0.06 | 4.53 | -1.70 | 1.12 |
| LM90514 | -0.06 | -0.27 | 1.06 | -0.13 | 1.75 | -6.17 | 0.50 | -0.57 |

There was a lack of consistency in ranking genotypes for average yield and heterosis. This could be seen for A/BTx631/(87EON366*90EON328)-LD30 which had the highest average yield at 5.04 t/ha but ranked thirteenth on heterosis at 65.15% for yield.

ICSR-939 had the best general combining ability at 0.88 followed by (87EON366*90EON328)-LD30 at 0.81 (Table 12). These two male lines combine better with both female lines on average than any other males. They are best for testing new female lines in a breeding program.

The hybrid ATx631/((TAM428*SV1)*CE151)-LD3 had the highest specific combing ability for yield at 1.42 , the highest high parent heterosis of 113.52% and was the second best yielding genotype averaging 4.93 t/ha (Tables 10, 11 and 12 respectively). This hybrid should be a candidate for immediate release in the target region since it outperformed all hybrids and popular regional varieties like Macia and Tegemeo. However ((TAM428*SV1)*CE151)-LD3 as a male parent had low general combining ability of -0.54 (Table 12) indicating that this line is good only in combination with ATx631. The highest yielding hybrid, ATx631/(87EON366*90EON328)-LD30, had a high parent heterosis of 65.15%, a specific combining ability of 0.84 (Tables 11 and 13 respectively). (87EON366*90EON328)-LD30 as a line had the second highest general combing ability for yield of 0.81 (Table 12). This hybrid should be considered for immediate release and its male parent can be used to test future A-lines. The discrepancy between these two hybrids indicates that the highest heterosis does not translate to the highest performance.

In this study grain yield is the most important trait. Based on the data herein, producers who grow an open pollinated variety could increase yields by 37% simply by choosing to grow an average hybrid.

Exsertion ranged from 1.33 cm for (90EON328*CE151)-LD6 to 18.06cm for ATx631/(LG70*ICSV400)-BE7 (Table 10). The two highest yielding genotypes A/BTx631/(87EON366*90EON328)-LD30 and A/BTx631/((TAM428*SV1)*CE151)-LD3 had exsertion values of 8.96 cm and 6.95 cm respectively. Check varieties Macia and Tegemeo had exsertion values of 8.67 cm and 4.82 cm respectively. This indicates that the two highest yielding genotypes are within the range for good panicle exsertion.

ATx635 hybrids had more exsertion than ATx631 hybrids as shown by the mean performance of their hybrids in Table 10 (13.2 cm compared to 12.54 cm respectively). The cross between ATx631 and (LG70*ICSV400)-BE7 had the highest specific combining ability at 4.05 (Table 13). Varieties with good panicle exsertion do not harbor pests in them. ATx635 hybrids had a higher constant parent heterosis of 44.64% compared to 31.8% for ATx631 hybrids (Table 11). (LG70*ICSV400)-BE7 also had the highest general combing ability of 3.68 (Table 12). This indicates that this line should be considered for use in improving exsertion since it had the best average exsertion, the best heterosis with ATx631 and the best general combing ability.

Height ranged from 113.59 cm for soberano to 229.47 cm for ATx631/((TAM428*SV1)*CE151)-LD3 (Table 10). Heterosis for height ranged from -28.31% for ATx631/Sureno to 70.31% for ATx631/(87EON366*90EON328)-LD30 (Table 11). The two highest yielding genotypes A/BTx631/(87EON366*90EON328)-

LD30 and A/BTx631/((TAM428*SV1)*CE151)-LD3 had plant height values of 224.86 cm and 229.47 cm respectively. Check varieties Macia and Tegemeo had exsertion values of 152.93 cm and 156.83 cm respectively. Farmers in Southern Africa are not highly mechanized like the farmers in the developed world. They still prefer taller cultivars for ease of harvest. The height of these hybrids would be acceptable for these farmers if they are compared to the commonly grown photoperiod sensitive local landrace cultivars. Desired height will vary depending on the choices of the farmers in the target area. The two highest yielding genotypes are within good range for plant height.

DMA ranged from 61.78 for (M84-7*WSV387)-HD7 to 84.11 for LM89537 (Table 10). Heterosis for DMA ranged from -6.53 for ATx631/Tegemeo to 28.6 for ATx631/(M84-7*WSV387)-HD7 (Table 11). The two highest yielding genotypes A/BTx631/(87EON366*90EON328)-LD30 and A/BTx631/((TAM428*SV1)*CE151)-LD3 had DMA values of 80.67 days and 80.33 days respectively. Check varieties Macia and Tegemeo had exsertion values of 81.44 days and 83.89 days respectively. This indicates that the best hybrids flowered slightly earlier than the checks.

ATx635 resulted in hybrids that are earlier flowering than ATx631 (78.2 days compared to 79.5 days respectively) (Table 10). Tegemeo had the best general combining ability at -1.63 (Table 12). This indicates that Tegemeo is the best tester for reducing maturity. The cross between (TAM428*SV1)*CE151)-LD3 and ATx635 had the highest specific combining ability for DMA at -2.28% (Table 13).

A level of heterosis of -0.02% in days to mid anthesis may seem small but is useful in developing adapted hybrids. This heterosis means that hybrids in this experiment flowered or matured earlier than their parents by 0.02% number of days. If crosses are done with more strategically selected parents i.e. with proper parent selection targeted at reducing flowering or maturation time, DMA can be significantly reduced. This would mean that farmers would spend less time scaring birds in the fields and they would have a crop to eat earlier in time to avoid starvation.

**G x E interaction**

The biplot uses the performance of genotypes to classify environments. The four environments caused varying responses for yield among the genotypes as shown in the graphical display of the nature of the genotype by environment interactions (Figure 2). All environments are in different quadrates indicating that each environment was unique. However, Zambia is completely different from the other three environments as seen by its distended position from the other three locations on the biplot.

Most genotypes are closer to the origin indicating that they are more stable. Genotypes 62, 34 and 69 namely (ATx631/(WSV387*((CE151*BDM499)-LD17)), Tx635/(Sureno*SRN39)-BE1, and ATx631/ICSV1089BF performed well in Zambia because they are in the Zambian quadrate and positioned closer to Zambia than the origin. The three genotypes (62, 34 and 69) performed relatively poorly in Weslaco since their position on the biplot is directly opposite to Weslaco. Genotype 31 ATx635/((TAM428*SV1)*CE151)-LD3, performed well in Zambia but it was less stable than others in that sector because it is further from the origin and from the line from the origin to Zambia. Genotype 3 (RTx436) performed well in College Station and genotype 7 (LM90538) performed well in Weslaco. Most genotypes in the Halfway sector are too close to the origin indicating that they performed well across all environments.

According to Figure 3 the performance of genotypes for plant height at Weslaco and Halfway was very similar since both locations are within the same quadrate. College Station and Zambia fell in different quadrates implying that environmental conditions in the two locations caused different responses in these genotypes. Most genotypes are closer to the origin indicating that most genotypes performed averagely well in all the four environments.

Genotype 16 (90EON328*CE151)-LD6, performed very well in College Station whereas genotypes 21 and 55 namely (LG70*ICSV400)-BE7 and ATX631*RTx436 performed well in both College Station and Halfway judging from their intermediate position between the two locations. Genotypes 28, 6 and 24 namely LM90514, (Sureno*86EON362), and Soberano performed well in both Weslaco and Halfway. Genotypes 61, 57 and 62 namely ATx631/(87EON366*90EON328)-LD30, ATx631/((TAM428*SV1)*CE151)-LD3, and ATx631/(WSV387*((CE151*BDM499)-LD17)) performed well in Zambia.

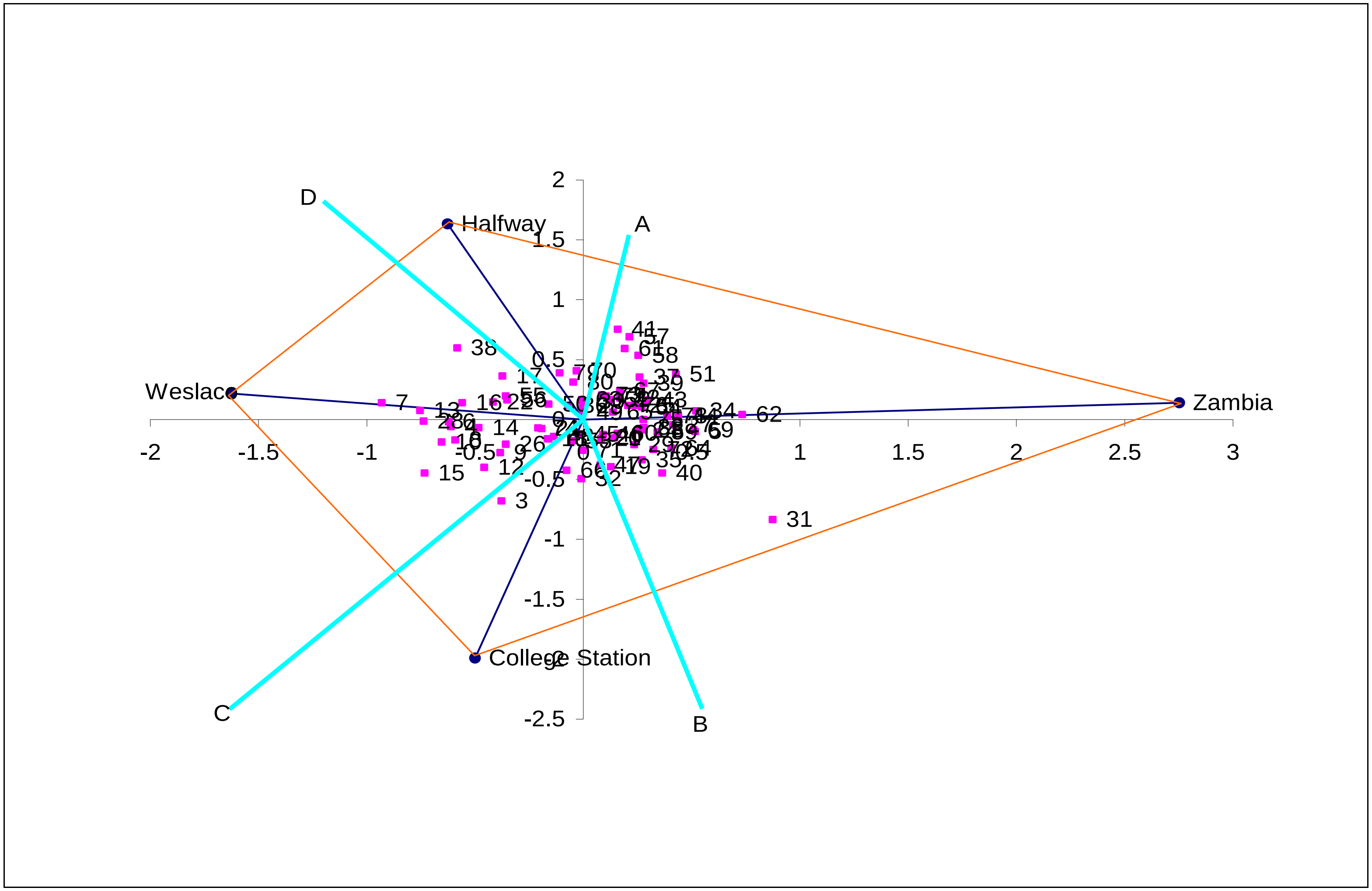


**Figure 2.** Biplot showing yield response of all eighty genotypes (parents 1 to 28 and hybrids 29 to 80) to differences in the four environments (College Station, Weslaco, Halfway and Zambia) in 2004.

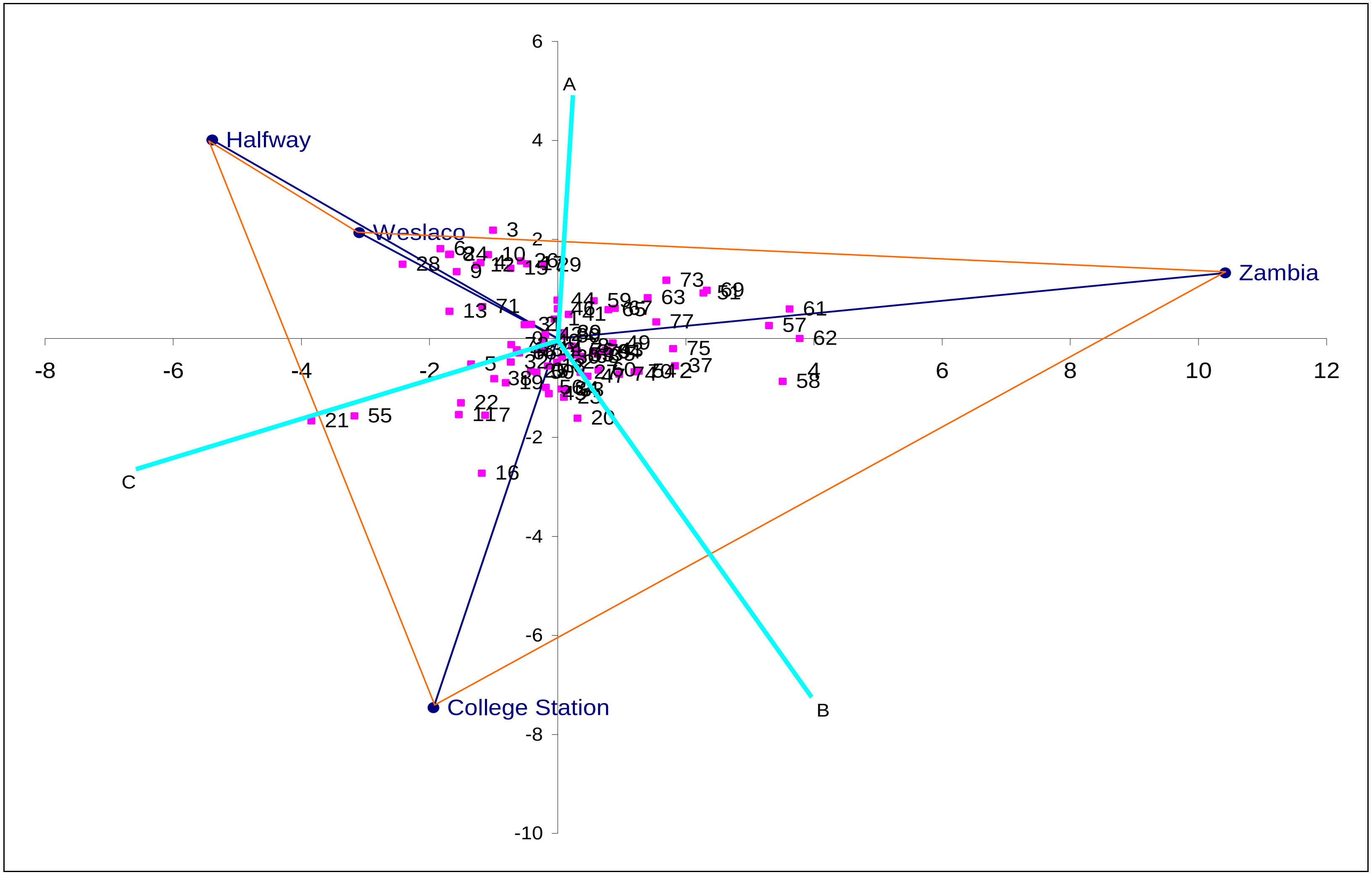


**Figure 3.** Biplot showing height response of all eighty genotypes (parents 1 to 28 and hybrids 29 to 80) to differences in the four environments (College Station, Weslaco, Halfway and Zambia) in 2004.

**Food quality analysis**

Several factors affect the outward appearance of sorghum grain. The genetics of pericarp color, pericarp thickness, the presence of a testa, color and thickness of testa, and endosperm color all interact to determine sorghum grain color (Rooney et al. 1980). All of these genotypes do not have a testa and are group I sorghums according to the classification defined by Price and Butler (1977). They are all food type sorghums but white seeded genotypes will be preferred to non white.

Samples taken from one parent line (ICSR939) and one hybrid (ATx631/ICSV-LM89510) were not large enough for analysis and thus are not included in this analysis. Among the remaining entries, there were highly significant differences among genotypes for the kernel hardness index, Hunter's L, a, and b values, test weight, protein and starch content (Table 14).

**Table 14.** Analysis of variance for TADD (hardness index values), LAB (l-values), prot (% protein content), and starch (% starch content) for all genotypes on grain harvested from Halfway in 2004.

| Source | DF | TADD† | DF | LAB† | twt† | DF | prot† | starch† |
|---|---|---|---|---|---|---|---|---|
| Rep | 1 | 0.046731$^{ns}$ | 2 | 2.00* | 0.3347$^{ns}$ | 2 | 0.3655$^{ns}$ | 0.2719$^{ns}$ |
| Genotype | 77 | 7079.5734** | 77 | 3760.47** | 815.099** | 77 | 509.735** | 839.924** |
| Error | 77 | 70.291 | 154 | 37.64 | 47.196 | 153 | 11.77 | 38.648 |
| Total | 155 | 7149.91 | 233 | 3800.11 | 862.63 | 232 | 521.84 | 878.861 |
| | | | | | | | | |
| R-Square | - | 0.99 | - | 0.99 | 0.95 | - | 0.98 | 0.96 |
| CV (%) | - | 1.18 | - | 0.85 | 0.92 | - | 2.37 | 0.70 |
| Mean | - | 81.13 | - | 58.36 | 59.75 | - | 11.69 | 72.13 |

* ,** Significant at the 0.01, and 0.05 probability levels, respectively.
† Based on Type III Sums of Square.

The hardness index as measured with a TADD machine (TADD) is very important because it indicates how much grain would remain after dehulling whole sorghum grain with a mortar and pestle before further processing. The higher the grain yield after dehulling the better because there will be less wastage. TADD hardness ranged from a low of 53.18 for ATx631/LM90538 to 89.3 for ATx635/ICSV1089BF (Table 15). From the observed range for TADD hardness indices, these genotypes were classified into hard endosperm genotypes with indices ranging from 80 to 90, intermediate endosperm genotypes with indices ranging from 75 to 80 and soft endosperm genotypes with indices less than 75. This classification was based on combining TADD hardness with SKHT hardness and visual scoring results (discussed later). The two highest yielding genotypes ATx631/(87EON366*90EON328)-LD30 and ATx631/ ((TAM428*SV1)* CE151)-LD3 scored 77.6 and 80.15 indices making them intermediate and hard endosperm genotypes respectively.

**Table 15.** Means for TADD (hardness index), LAB (Hunter's l-values), twt (test weight in $g/cm^{-3}$), prot (% protein content) and starch (% starch content), hard (hardness index measured using a Single kernel Hardness Tester), skwt (single kernel weight in µg), and dia (single kernel diameter in mm) for all eighty genotypes from grain harvested at Halfway in 2004.

| Pedigree | Gen | tadd | LAB | twt | prot | starch | hard | skwt | dia |
|---|---|---|---|---|---|---|---|---|---|
| ICSR-939 | 25 | . | . | . | . | . | 68.64 | 35.66 | 2.67 |
| ATx631/ICSV-LM89510 | 66 | . | . | . | . | . | 92.79 | 24.73 | 1.98 |
| ATx635/ICSV1089BF | 43 | 89.30 | 60.42 | 61.28 | 13.74 | 70.79 | 61.06 | 33.33 | 2.53 |
| Sureno | 19 | 88.75 | 60.00 | 60.94 | 13.57 | 70.41 | 71.78 | 30.78 | 2.48 |
| ATx635/(87EON366*WSV387)-HD25 | 38 | 88.63 | 60.30 | 60.84 | 11.33 | 73.51 | 85.74 | 26.07 | 2.25 |
| ATx635/Sureno | 45 | 88.30 | 61.64 | 62.30 | 10.59 | 72.97 | 84.64 | 28.55 | 2.23 |
| ATx635/JOCORO | 49 | 88.03 | 61.47 | 61.28 | 11.61 | 71.99 | 79.86 | 32.70 | 2.43 |
| ATx635/(87EON366*TAM428)-HF4 | 37 | 87.95 | 59.36 | 61.92 | 11.39 | 73.85 | . | . | . |
| ICSV1089BF | 17 | 87.70 | 57.88 | 62.01 | 15.67 | 68.15 | 62.70 | 27.95 | 2.44 |
| ATx635/(WSV387*((CE151*BDM499)-LD17)) | 36 | 87.23 | 58.93 | 59.60 | 12.72 | 71.51 | 82.16 | 28.38 | 2.31 |
| ATx631/Sureno | 71 | 87.18 | 61.50 | 62.75 | 9.88 | 73.08 | 79.72 | 29.13 | 2.36 |
| Macia | 18 | 87.05 | 60.08 | 60.68 | 10.14 | 73.90 | 81.68 | 30.01 | 2.52 |
| ATx635/(LG70*ICSV400)-BE7 | 47 | 86.75 | 59.63 | 60.75 | 12.10 | 72.14 | 87.36 | 29.86 | 2.30 |
| ATx631/Macia | 70 | 86.65 | 62.36 | 61.42 | 10.12 | 72.88 | 70.31 | 30.32 | 2.44 |
| ICSV-LM89510 | 14 | 86.63 | 58.24 | 61.87 | 12.89 | 70.56 | 83.72 | 29.65 | 2.42 |
| ATx631/ICSV1089BF | 69 | 86.25 | 61.33 | 61.14 | 10.59 | 72.86 | . | . | . |
| ATx635/Tegemeo | 46 | 86.15 | 60.68 | 61.33 | 11.41 | 72.60 | 77.51 | 34.21 | 2.54 |
| ATx635/(90EON328*(S35*ICSV401))-BE1 | 41 | 85.93 | 60.27 | 62.11 | 10.78 | 73.68 | 84.92 | 26.71 | 2.25 |
| ATx635/(Sureno*86EON362) | 32 | 85.90 | 60.04 | 60.25 | 13.83 | 70.11 | 88.51 | 25.64 | 2.29 |
| ATx635/(90EON328*CE151)-LD6 | 42 | 85.83 | 59.45 | 61.03 | 11.79 | 72.69 | 58.39 | 38.69 | 2.79 |
| ATx635/CE151-262-A1 | 39 | 85.68 | 59.29 | 59.52 | 10.91 | 72.71 | 68.33 | 35.46 | 2.59 |
| ((TAM428*SV1)*CE151)-LD3 | 5 | 85.63 | 58.45 | 59.66 | 10.79 | 74.16 | 61.20 | 32.92 | 2.60 |
| ATx635/(Sureno*SRN39)-BE1 | 34 | 85.43 | 58.92 | 59.91 | 13.31 | 71.10 | 69.37 | 35.01 | 2.69 |
| ATx635/Macia | 44 | 85.30 | 61.54 | 60.82 | 11.62 | 71.75 | 79.38 | 29.32 | 2.37 |
| ATx631/JOCORO | 75 | 85.30 | 61.42 | 61.28 | 10.37 | 73.25 | . | . | . |

**Table 15**. Continued.

| Pedigree | Gen | tadd | LAB | twt | prot | starch | hard | skwt | dia |
|---|---|---|---|---|---|---|---|---|---|
| (LG70*ICSV400)-BE7 | 21 | 85.13 | 56.17 | 58.52 | 14.06 | 69.42 | 83.76 | 29.52 | 2.54 |
| ATx635/((TAM428*SV1)*CE151)-LD3 | 31 | 85.05 | 58.31 | 59.71 | 11.57 | 72.40 | 75.75 | 29.88 | 2.54 |
| (Sureno*86EON362) | 6 | 84.90 | 57.93 | 59.92 | 12.99 | 70.38 | 82.43 | 27.44 | 2.40 |
| B.Tx635 | 1 | 84.88 | 58.41 | 60.60 | 13.49 | 70.91 | 53.40 | 28.69 | 2.54 |
| ATx635/(87EON366*90EON328)-LD30 | 35 | 84.80 | 60.05 | 60.09 | 11.07 | 72.36 | 83.38 | 29.51 | 2.49 |
| ATx635/Soberano | 50 | 84.63 | 57.56 | 61.26 | 11.05 | 73.79 | 85.88 | 26.67 | 2.21 |
| ATx635/(Macia*TAM428)-LL14 | 52 | 84.43 | 60.38 | 60.21 | 11.20 | 73.63 | 81.63 | 34.05 | 2.52 |
| ATx635/ICSV-LM89510 | 40 | 84.23 | 60.88 | 62.90 | 11.33 | 72.94 | 76.29 | 32.60 | 2.45 |
| ATx631/(87EON366*WSV387)-HD25 | 64 | 83.95 | 59.54 | 59.94 | 11.45 | 73.47 | 80.88 | 31.68 | 2.34 |
| LM89537 | 27 | 83.53 | 58.10 | 59.13 | 12.84 | 70.57 | 80.35 | 24.81 | 2.35 |
| (Sureno*SRN39)-BE1 | 8 | 83.48 | 57.33 | 58.57 | 13.59 | 69.25 | 82.27 | 29.82 | 2.53 |
| Tegemeo | 20 | 83.43 | 58.64 | 59.17 | 15.10 | 69.31 | 82.04 | 27.21 | 2.33 |
| (87EON366*WSV387)-HD25 | 12 | 83.30 | 57.11 | 59.50 | 11.70 | 72.64 | 77.57 | 31.97 | 2.34 |
| ATx635/(M84-7*WSV387)-HD7 | 48 | 83.23 | 61.01 | 60.99 | 11.07 | 72.53 | 88.39 | 27.07 | 2.03 |
| ATx631/LM89537 | 79 | 82.73 | 61.51 | 60.90 | 9.61 | 74.24 | 67.73 | 33.67 | 2.49 |
| ATx631/(87EON366*TAM428)-HF4 | 63 | 82.63 | 58.13 | 60.36 | 10.80 | 72.87 | 81.56 | 33.93 | 2.30 |
| (Macia*TAM428)-LL14 | 26 | 82.53 | 59.73 | 61.14 | 11.09 | 73.45 | 80.49 | 30.50 | 2.41 |
| ATx631/CE151-262-A1 | 65 | 82.30 | 58.84 | 61.16 | 12.05 | 71.61 | 90.46 | 27.42 | 2.22 |
| ATx631/Tegemeo | 72 | 81.85 | 60.49 | 61.60 | 9.91 | 73.89 | 84.05 | 24.73 | 2.07 |
| Soberano | 24 | 81.80 | 54.47 | 59.31 | 11.33 | 73.73 | 78.24 | 31.46 | 2.33 |
| ATx635/ICSR-939 | 51 | 81.75 | 59.26 | 60.20 | 11.22 | 72.02 | 94.84 | 25.71 | 2.16 |
| ATx631/(Sureno*86EON362) | 58 | 81.28 | 59.51 | 60.58 | 9.96 | 73.56 | 76.45 | 31.01 | 2.49 |
| ATX635*RTx437 | 30 | 81.23 | 57.07 | 60.58 | 11.43 | 72.65 | 84.48 | 26.62 | 2.40 |
| ATx635/LM89537 | 53 | 81.23 | 60.78 | 60.05 | 10.15 | 72.86 | 89.63 | 28.17 | 2.28 |
| Jocoro | 23 | 81.20 | 57.82 | 58.06 | 13.24 | 70.48 | 84.51 | 27.45 | 2.38 |
| (M84-7*WSV387)-HD7 | 22 | 80.98 | 60.55 | 59.83 | 12.37 | 71.75 | 72.77 | 33.66 | 2.65 |
| ATx631/(90EON328*(S35*ICSV401))-BE1 | 67 | 80.90 | 60.20 | 62.55 | 10.62 | 73.74 | 85.14 | 27.98 | 2.14 |
| (87EON366*TAM428)-HF4 | 11 | 80.80 | 57.13 | 59.24 | 12.64 | 71.73 | 86.88 | 24.81 | 2.29 |
| LM90514 | 28 | 80.30 | 57.44 | 59.18 | 11.46 | 71.96 | 76.07 | 28.59 | 2.49 |
| ATx631/((TAM428*SV1)*CE151)-LD3 | 57 | 80.15 | 58.62 | 60.19 | 10.92 | 72.21 | 89.67 | 22.91 | 2.18 |
| ATx631/(Sureno*SRN39)-BE1 | 60 | 80.03 | 58.44 | 59.41 | 11.32 | 72.26 | 82.87 | 27.20 | 2.17 |

**Table 15**. Continued.

| Pedigree | Gen | tadd | LAB | twt | prot | starch | hard | skwt | dia |
|---|---|---|---|---|---|---|---|---|---|
| ATx631/SOBERANO | 76 | 79.98 | 56.11 | 59.78 | 11.16 | 73.36 | 78.57 | 33.48 | 2.38 |
| ATx631/LM90514 | 80 | 79.45 | 59.62 | 59.54 | 11.87 | 72.38 | 78.54 | 31.47 | 2.49 |
| (WSV387*((CE151*BDM499)-LD17)) | 10 | 79.25 | 58.06 | 59.42 | 12.21 | 73.15 | 72.74 | 32.85 | 2.60 |
| ATx631/(M84-7*WSV387)-HD7 | 74 | 79.10 | 62.37 | 60.46 | 9.73 | 75.52 | 86.97 | 25.49 | 2.21 |
| ATx631/(WSV387*((CE151*BDM499)-LD17)) | 62 | 79.08 | 61.11 | 59.74 | 10.23 | 73.73 | 83.08 | 25.74 | 2.17 |
| ATx631/(Macia*TAM428)-LL14 | 78 | 78.68 | 60.07 | 60.18 | 11.39 | 72.71 | 77.83 | 31.58 | 2.32 |
| ATX631*RTx436 | 55 | 78.35 | 58.34 | 58.89 | 10.20 | 74.00 | 77.09 | 31.30 | 2.36 |
| R.Tx436 | 3 | 78.08 | 57.94 | 57.31 | 12.24 | 72.08 | 83.56 | 23.52 | 2.13 |
| ATx631/(87EON366*90EON328)-LD30 | 61 | 77.60 | 60.17 | 58.41 | 9.59 | 73.87 | 74.09 | 30.52 | 2.41 |
| CE151-262-A1 | 13 | 77.48 | 56.05 | 57.91 | 12.10 | 71.25 | 71.60 | 33.99 | 2.52 |
| ATx635/LM90514 | 54 | 76.25 | 61.13 | 57.29 | 11.15 | 72.27 | 86.23 | 25.21 | 2.16 |
| ATx631/ICSR-939 | 77 | 74.63 | 60.06 | 59.89 | 10.13 | 74.44 | 86.44 | 26.84 | 2.18 |
| ATx631/(90EON328*CE151)-LD6 | 68 | 73.25 | 59.44 | 58.20 | 11.27 | 72.64 | 87.44 | 27.95 | 2.30 |
| ATx635/LM90538 | 33 | 73.13 | 45.07 | 58.05 | 13.52 | 68.87 | 75.23 | 32.56 | 2.67 |
| (90EON328*CE151)-LD6 | 16 | 72.03 | 57.26 | 54.59 | 15.17 | 67.67 | 38.59 | 30.35 | 2.59 |
| R.TX437 | 4 | 71.35 | 54.20 | 57.73 | 11.71 | 72.68 | 68.48 | 30.67 | 2.52 |
| ATX631*RTX437 | 56 | 71.30 | 57.11 | 59.13 | 10.29 | 74.29 | 88.53 | 25.48 | 2.19 |
| ATX635*RTx436 | 29 | 71.13 | 57.59 | 56.81 | 9.79 | 73.83 | 91.77 | 24.13 | 2.24 |
| (90EON328*(S35*ICSV401))-BE1 | 15 | 67.55 | 37.85 | 55.08 | 13.96 | 67.15 | 45.88 | 30.54 | 2.48 |
| B.Tx631 | 2 | 60.95 | 60.72 | 55.35 | 9.69 | 72.91 | 87.44 | 23.07 | 2.19 |
| LM90538 | 7 | 56.75 | 42.88 | 52.73 | 16.44 | 64.15 | 64.97 | 31.96 | 2.66 |
| ATx631/LM90538 | 59 | 53.18 | 46.30 | 55.47 | 12.88 | 68.64 | 87.93 | 24.44 | 2.17 |
| Overall Means | - | 81.13 | 58.36 | 59.75 | 11.69 | 72.13 | 78.21 | 29.58 | 2.39 |

**Table 15**. Continued.

| Pedigree | Gen | tadd | LAB | twt | prot | starch | hard | skwt | dia |
|---|---|---|---|---|---|---|---|---|---|
| Mean of Parents | - | 86.64 | 59.83 | 60.88 | 11.91 | 72.03 | 76.87 | 30.48 | 2.44 |
| Mean of Hybrids | - | 78.29 | 57.55 | 59.17 | 11.62 | 72.16 | 79.35 | 28.89 | 2.35 |
| Mean of ATx635 | - | 82.59 | 58.92 | 60.27 | 11.61 | 72.38 | 81.66 | 29.22 | 2.36 |
| Mean of ATx631 | - | 73.42 | 56.00 | 57.92 | 11.64 | 71.90 | 80.83 | 28.52 | 2.35 |
| Mean of all males | - | 86.64 | 59.83 | 60.88 | 11.91 | 72.03 | 76.53 | 30.50 | 2.45 |
| Heterosis (Parents vs Hybrids) % | - | 2.50 | 4.74 | 2.60 | -12.35 | 2.57 | 9.62 | -0.10 | -4.49 |
| R-square | - | 0.99 | 0.99 | 0.95 | 0.98 | 0.96 | - | - | - |
| CV (%) | - | 1.18 | 0.85 | 0.93 | 2.37 | 0.70 | - | - | - |
| LSD (0.05) | - | 1.90 | 0.80 | 0.89 | 0.45 | 0.81 | - | - | - |

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Check varieties Macia and Tegemeo scored 87.05 and 83.43 respectively. Both high yielding genotypes seem hard enough even though ATx631/(87EON366*90EON328)-LD30 may need more hardening. A marginal 2.5% heterosis for TADD was exhibited by these genotypes indicating that hybrids had harder grains than parental lines. The cross between ATx631 and ICSR-939 had the highest heterosis of 22.44% and the cross between ATx635 and RTx436 had the lowest heterosis of -16.2% (Table 16). Mean hardness for hybrids (81.82) was higher than mean hardness for both males (79.83) and females [(84.13 + 79.41)/2 = 81.77]. This shows over dominant gene action for grain hardness. ATx635 was harder than ATx631 (84.88 compared to 60.95 respectively). On average ATx635 hybrids were harder than ATx631 hybrids (84.13 compared to 79.41 respectively) as expected since this trait exhibits overdominant gene action.

The hardness index as measured with a Single Kernel Hardness Tester (HARD) ranged from a high of 94.84 from a cross between ATx635 and ICSR-939 to a low of 38.59 for (90EON328*CE151)-LD (Table 15).

There was a marginal heterosis of 9.62% indicating that hybrids had harder grains than parental lines. This method also indicted that ATx635 is harder than ATx631 (87.44 compared to 53.4 respectively). Mean hardness for hybrids (81.24) was equal to mean hardness of females [(81.66+80.83)/2 = 81.24]. This shows dominant gene action for grain hardness. ATx635 hybrids were harder than ATx631 hybrids according to this method (81.66 compared to 80.83 respectively). This method of measuring hardness confirms the results from the TADD method. Both methods of measuring hardness were also highly correlated with a Pearson correlation coefficient of 0.87** (Table 17).

The whiter the grain the lighter the color of the products from its grain and the more acceptable is the variety. Hunter's L values ranged from 37.85 for (90EON328*(S35*ICSV401))-BE1 to 62.37 for ATx631/(M84-7*WSV387)-HD7 (Table 15). Macia is a very successful cultivar in the Southern Africa region and has an average L value of 60.08.

**Table 16.** High parent heterosis for TADD (hardness index), LAB (Hunter's l-values), twt (test weight in g/cm$^{-3}$), prot (% protein content) and starch (% starch content) for all fifty two hybrids from grain harvested at Halfway in 2004.

| Pedigree | Gen | tadd | LAB | twt | prot | starch |
|---|---|---|---|---|---|---|
| ATX635*RTx436 | 29 | -16.20 | -1.42 | -6.25 | -27.45 | 2.43 |
| ATX635*RTx437 | 30 | -4.30 | -5.74 | -0.03 | -15.30 | -0.04 |
| ATx635/((TAM428*SV1)*CE151)-LD3 | 31 | -0.67 | -0.24 | -1.46 | -14.21 | -2.38 |
| ATx635/(Sureno*86EON362) | 32 | 1.18 | 2.79 | -0.58 | 2.50 | -1.12 |
| ATx635/LM90538 | 33 | -13.84 | -22.84 | -4.20 | -17.74 | -2.88 |
| ATx635/(Sureno*SRN39)-BE1 | 34 | 0.65 | 0.87 | -1.13 | -2.11 | 0.27 |
| ATx635/(87EON366*90EON328)-LD30 | 35 | -0.09 | 2.80 | -0.83 | -17.91 | 1.23 |
| ATx635/(WSV387*((CE151*BDM499)-LD17)) | 36 | 2.77 | 0.89 | -1.64 | -5.73 | -2.24 |
| ATx635/(87EON366*TAM428)-HF4 | 37 | 3.62 | 1.62 | 2.19 | -15.59 | 2.96 |
| ATx635/(87EON366*WSV387)-HD25 | 38 | 4.42 | 3.23 | 0.40 | -15.99 | 1.20 |
| ATx635/CE151-262-A1 | 39 | 0.94 | 1.50 | -1.78 | -19.13 | 2.04 |
| ATx635/ICSV-LM89510 | 40 | -2.77 | 4.22 | 3.80 | -15.99 | 2.86 |
| ATx635/(90EON328*(S35*ICSV401))-BE1 | 41 | 1.24 | 3.18 | 2.49 | -20.09 | 3.91 |
| ATx635/(90EON328*CE151)-LD6 | 42 | 1.12 | 1.77 | 0.72 | -12.63 | 2.51 |
| ATx635/ICSV1089BF | 43 | 1.82 | 3.44 | 1.12 | 1.85 | -0.16 |
| ATx635/Macia | 44 | -2.01 | 2.42 | 0.24 | -13.86 | -2.90 |
| ATx635/Sureno | 45 | -0.51 | 2.73 | 2.24 | -21.52 | 2.91 |
| ATx635/Tegemeo | 46 | 1.50 | 3.48 | 1.21 | -15.42 | 2.39 |
| ATx635/(LG70*ICSV400)-BE7 | 47 | 1.91 | 2.08 | 0.25 | -10.28 | 1.73 |
| ATx635/(M84-7*WSV387)-HD7 | 48 | -1.94 | 8.61 | 0.64 | -17.94 | 1.09 |
| ATx635/JOCORO | 49 | 3.71 | 5.23 | 1.12 | -13.91 | 1.53 |
| ATx635/SOBERANO | 50 | -0.29 | -1.46 | 1.09 | -18.06 | 0.08 |
| ATx635/ICSR-939 | 51 | -3.68 | 1.46 | -0.65 | -16.85 | 1.57 |
| ATx635/(Macia*TAM428)-LL14 | 52 | -0.53 | 3.36 | -0.64 | -16.98 | 0.25 |
| ATx635/LM89537 | 53 | -4.30 | 4.05 | -0.91 | -24.76 | 2.75 |
| ATx635/LM90514 | 54 | -10.16 | 4.65 | -5.46 | -17.37 | 0.43 |
| ATX631*RTx436 | 55 | 0.35 | -3.93 | 2.76 | -16.64 | 1.50 |
| ATX631*RTX437 | 56 | -0.07 | -5.95 | 2.41 | -12.10 | 1.90 |
| ATx631/((TAM428*SV1)*CE151)-LD3 | 57 | -6.39 | -3.47 | 0.89 | 1.17 | -0.95 |
| ATx631/(Sureno*86EON362) | 58 | -4.27 | -1.99 | 1.11 | -23.35 | 0.90 |
| ATx631/LM90538 | 59 | -6.30 | -23.75 | 5.18 | -21.63 | -5.85 |

**Table 16.** Continued.

| Pedigree | Gen | tadd | LAB | twt | prot | starch |
|---|---|---|---|---|---|---|
| ATx631/(Sureno*SRN39)-BE1 | 60 | -4.13 | -3.76 | 1.44 | -16.72 | -0.89 |
| ATx631/(87EON366*90EON328)-LD30 | 61 | -2.85 | -0.91 | -0.97 | -12.26 | 1.32 |
| ATx631/(WSV387*((CE151*BDM499)-LD17)) | 62 | -0.22 | 0.63 | 0.53 | -16.22 | 0.80 |
| ATx631/(87EON366*TAM428)-HF4 | 63 | 2.26 | -4.28 | 1.90 | -14.58 | -0.05 |
| ATx631/(87EON366*WSV387)-HD25 | 64 | 0.78 | -1.94 | 0.75 | -2.19 | 0.77 |
| ATx631/CE151-262-A1 | 65 | 6.23 | -3.10 | 5.62 | -0.41 | -1.78 |
| ATx631/ICSV-LM89510 | 66 | . | . | . | . | . |
| ATx631/(90EON328*(S35*ICSV401))-BE1 | 67 | 19.76 | -0.86 | 13.56 | -23.95 | 1.14 |
| ATx631/(90EON328*CE151)-LD6 | 68 | 1.70 | -2.11 | 6.61 | -25.69 | -0.36 |
| ATx631/ICSV1089BF | 69 | -1.65 | 1.00 | -1.41 | -32.40 | -0.06 |
| ATx631/Macia | 70 | -0.46 | 2.70 | 1.22 | -0.13 | -1.38 |
| ATx631/Sureno | 71 | -1.77 | 1.28 | 2.97 | -27.19 | 0.24 |
| ATx631/Tegemeo | 72 | -1.89 | -0.38 | 4.11 | -34.33 | 1.35 |
| ATx631/(LG70*ICSV400)-BE7 | 73 | -6.55 | -1.02 | 3.05 | -25.20 | 0.92 |
| ATx631/(M84-7*WSV387)-HD7 | 74 | -2.32 | 2.72 | 1.05 | -21.32 | 3.58 |
| ATx631/JOCORO | 75 | 5.05 | 1.14 | 5.56 | -21.68 | 0.47 |
| ATx631/SOBERANO | 76 | -2.23 | -7.60 | 0.79 | -1.47 | -0.50 |
| ATx631/ICSR-939 | 77 | 22.44 | -1.09 | 8.19 | 4.50 | 2.11 |
| ATx631/(Macia*TAM428)-LL14 | 78 | -4.67 | -1.08 | -1.56 | 2.71 | -1.01 |
| ATx631/LM89537 | 79 | -0.96 | 1.30 | 3.00 | -25.18 | 1.83 |
| ATx631/LM90514 | 80 | -1.06 | -1.82 | 0.60 | 3.61 | -0.73 |
| | | | | | | |
| CPH A/BTx.635 | | -1.40 | 1.26 | -0.31 | -14.71 | 0.86 |
| CPH A/BTx.631 | | 0.43 | -2.33 | 2.77 | -14.51 | 0.21 |

**Table 17.** Pearson coefficients of correlation for HARD (hardness index from a Single Kernel Hardness Tester), SKWT (single kernel weight), DIA (single kernel diameter), TWT (test weight), Yield (grain yield in t/ha), and TADD (hardness index from a TADD machine).

| | HARD | SKWT | DIA | TWT | TADD |
|---|---|---|---|---|---|
| HARD | | | | | |
| SKWT | -0.596** | | | | |
| DIA | -0.715** | 0.796** | | | |
| TWT | 0.624** | -0.220$^{ns}$ | -0.364** | | |
| TADD | 0.869** | -0.312** | -0.479** | 0.796** | |
| Yield | 0.196$^{ns}$ | 0.02$^{ns}$ | -0.19$^{ns}$ | 0.199$^{ns}$ | 0.11$^{ns}$ |

** Correlation significant at the 0.01 level (2-tailed).
$^{ns}$ Not significant.

All hybrids with L values larger than Macia values should be considered acceptable, if not better than Macia. From visual observation of samples, values from as low as 55 are also acceptable. The highest yielding genotypes ATx631/(87EON366*90EON328)-LD30 and ATx631/ ((TAM428*SV1)* CE151)-LD3 had L values of 60.17 and 58.62 respectively. Both hybrids have acceptable whiteness to consumers in the region. This trait showed a marginal heterosis of 4.74 % indicating that hybrids had whiter grains than parental lines. ATx631 grain is whiter than ATx635 grain with an average L value of 60.72 compared to 58.41 for ATx635. ATx631 hybrids were marginally whiter than ATx635 hybrids as shown by the means for hybrids. Heterosis for L values ranged from a high of 8.61% for ATx635/(M84-7*WSV387)-HD7 to -23.61% for ATx631/LM90538.

Test weight values are a function of several factors, including kernel density, shape and packing ability. In general the higher the test weight value, the higher the energy and quality potential. Test weight values ranged from 52.73 g/cm$^{-3}$ for LM90538 to 62.90 g/cm$^{-3}$ for ATx635/ICSV-LM89510 averaging 59.75 g/cm$^{-3}$ (Table 15). This trait had a marginal heterosis of 2.6% indicating that hybrids had higher test weights than parents. The highest yielding genotypes ATx631/(87EON366*90EON328)-LD30 and ATx631/ ((TAM428*SV1)* CE151)-LD3 had test weight values of 58.41 g/cm$^{-3}$ and 60.19 g/cm$^{-3}$ respectively. Check varieties Macia and Tegemeo had test weight values of 60.68 g/cm$^{-3}$ and 59.17 g/cm$^{-3}$ respectively. This indicates that the two highest yielding genotypes are within the acceptable range for test weight.

ATx635 had a higher test weight than ATx631 (60.43 compared to 60.13 respectively). Mean test weight for hybrids (60.28) was equal to the mean test weight for females [(60.13+60.43)/2 =60.28] and higher than for males (58.76). This shows completely dominant gene action for test weight.

Across all entries, protein content averaged 11.69% (Table 15) and this is within the range obtained from previous research (Hulse et al 1980, Serna-Saldivar and Rooney 1991). Sorghum protein content is influenced by environmental conditions (planting date, temperatures, nitrogen content of the soil and cultivar) encountered during production (Klopfenstein and Hoseney 1995). Protein content ranged from 9.59% for ATx631/87EON366*90EON328)-LD30 to 16.44% for LM90538. Mean heterosis for protein content was negative at –12.35% indicating that hybrids had lower protein content than parental lines (Table 15). Previous research proved that in cereals grain yield is negatively correlated to protein content i.e. in sorghum (Hulse et al 1980) in wheat (Kibite and Evans, 1984) in maize (Gupta et al 1974). This is because an increase in yield for cereal grains is due to an increase in the starch stored in the endosperm during grain filling. This causes percent protein content to go down as grain yield grows. This experiment found a significant (at the 0.01 level) but not strong correlation of –0.35** between protein content and yield (not shown in any table but obtained using SPSS software).

The highest yielding genotypes ATx631/(87EON366*90EON328)-LD30 and ATx631/ ((TAM428*SV1)* CE151)-LD3 had protein content values of 9.59% and 10.92% respectively. Check varieties Macia and Tegemeo had protein content values of

10.14% and 15.1% respectively. This indicates that the two highest yielding genotypes had slightly lower protein content than Macia but significantly lower protein content than Tegemeo. The lower protein content is expected because yield is negatively related to protein content as shown above. Sorghum is eaten mainly as a source of carbohydrates and is always taken with meat or legumes as a source of proteins.

ATx635 had significantly higher protein content than ATx631 (13.49% compared to 9.69% respectively) and its hybrids had more proteins than ATx631 hybrids (11.6% compared to 10.67% for ATx631).

Starch content averaged 72.13% (Table 15) and it ranged from 64.15% for LM90538 to 75.52% for ATx631/(M84-7*WSV387)-HD7. This trait exhibited a marginal 2.57% heterosis indicating that hybrids had higher starch content than parental lines. The highest yielding genotypes ATx631/(87EON366*90EON328)-LD30 and ATx631/ ((TAM428*SV1)* CE151)-LD3 had starch content values of 73.87% and 72.21% respectively. Check varieties Macia and Tegemeo had protein content values of 73.9% and 69.31% respectively. This indicates that the two highest yielding genotypes starch content is within the acceptable range.

ATx631 had significantly more starch than ATx635 (72.91% compared to 70.91% respectively). ATx631 hybrids had more starch than ATx635 hybrids (73.16% compared to 72.37% respectively). ATx635 hybrids showed more heterosis for starch content than ATx631 hybrids (0.86 compared to 0.21 respectively) (Table 16).

All genotypes had a normal endosperm (non-waxy) hence the starch in them is expected to have 70 to 80% amylopectin and 20 to 30% amylose (Rooney and Serna-

Saldivar, 1991). The starch in sorghum is the main source of carbohydrate or energy for sorghum consumers. The packing of endosperm cells (with starch in them) plays a role in determining grain hardness. The corneous endosperm has a continuous strong bonded interface between the starch and protein whereas the floury endosperm has loosely packed endosperm cells (Rooney and Miller 1982).

The harder sorghum genotypes have a larger corneous endosperm than floury endosperm. This could be verified by looking at the pictures of longitudinal sections of hard, intermediate and soft endosperm types as shown in Figures 4 to 7. Visual hardness ratings as shown in these photographs were done following ratings as suggested by Rooney and Miller in 1982 and Single Kernel Hardness Tester (SKHT) ratings. Visual hardness ratings matched the hardness ratings that were obtained using the Single Kernel Hardness Tester. These two methods are therefore highly correlated.

Single kernel weight averaged 29.37 µg ranging from 38.69µg for ATx635/(90EON328*CE151)-LD6 to 22.91µg for ATx631/((TAM428*SV1)CE151)-LD3 (Table 15). Hybrids had lighter grain than parents (29.36 µg compared to 29.39 µg respectively). This is also indicated by a negative heterosis of -0.1%. However, hybrids yielded higher than parents (Table 10). This indicates that higher yields exhibited by hybrids over parents are due to hybrids producing more grain in the panicle than parents. ATx635 resulted in heavier grains than ATx631 (29.84 µg compared to 28.86 µg respectively).

Single kernel diameter averaged 2.38mm ranging from 2.79mm for ATx635/(90EON328*CE151)-LD6 to 1.98 mm for ATx631/ICSVLM89510 (Table 15).

Hybrids had smaller grains than parents (2.34mm compared to 2.45mm respectively). This is indicated by a negative heterosis of -4.49%. This further confirms that hybrids produced more grain in the panicle than parents. ATx635 resulted in hybrids with larger grains than ATx631 (2.39mm compared to 2.29mm respectively).

Test weight (twt) was highly correlated to TADD hardness (TADD) and Single Kernel Hardness Tester hardness (HARD) at 0.796** and 0.62** respectively (Table 17). This is as expected because higher test weight is an indication of more corneous endosperm than floury endosperm. This confirms earlier observation that hybrids had higher test weight and harder kernels than parents. These traits can therefore be improved simultaneously in a breeding program.

The strong negative correlation (-0.715**) between hardness measured using a Single Kernel Hardness Tester (HARD) and grain diameter (dia) seems to suggest that smaller kernels are harder than larger kernels. This confirms the earlier observation that hybrids had smaller and harder grains than parents. Improving hardness would imply reducing seed size

Kernel diameter (dia) was highly correlated to single kernel weight (skwt) at 0.796**. Bigger grains are expected to weigh more than smaller grains. Grain yield did not correlate with any of the quality traits. This means that grain yield can be improved simultaneously with any of these traits without any compromise since there is no correlation.

**Figure 4.** Median longitudinal half kernels of five soft endosperm sorghums [(90EON328*CE151)-LD6, LM90538, A/BTx631, A/BTx631/LM90538, and A/BTx631/(90EON328*CE151)-LD6], from top to bottom.

**Figure 5.** Median longitudinal half kernels of five intermediate endosperm sorghums [A/BTx631/(WSV387*((CE151*BDM499)-LD17), A/BTx631*R.Tx436, (90EON328*(S35*ICSV401))-BE1, A/BTx631*R.Tx437, and A/BTx631*LM90514], from top to bottom.

**Figure 6.** Median longitudinal half kernels of five hard endosperm sorghums [A/BTx635/JOCORO, ((TAM428*SV1)*CE151)-LD3, A/BTx635/(87EON366*TAM428)-HF4, SOBERANO, and SURENO], from top to bottom.

**Figure 7.** Check variety Macia.

# CHAPTER V

# CONCLUSION

ATx631 is a better female line for improving yield because its hybrids averaged 3.85 t/ha compared to ATx635 whose hybrids averaged 3.6 t/ha. This was because of the high heterosis exhibited by ATx631 in crosses as shown by the higher constant parent heterosis for ATx631 (41.03% compared to 35.22% for ATx635). ATx631 also had more hybrids in the top twenty than ATx635.

ICSR-939 and (87EON366*90EON328)-LD30 can be used as testers in breeding programs because they had the highest general combining ability. They can be used in the development of more female lines for further hybrid seed production. (LG70*ICSV400)-BE7 is a good line for improving panicle exsertion since it showed the highest heterosis (99.94%) with ATx631 and the best general and specific combining ability (3.68 and 4.05 respectively) for exsertion.

ATx635 is the best female line for improving grain hardness because its grain is harder than that of ATx631 (84.88 compared to 60.95 respectively) and this is transmitted to hybrids also.

Hybrids have smaller and harder grains than parents. The hybrid yield advantage is exhibited in having more grains on the panicle than parental lines.

Two hybrids, ATx631/(87EON366*90EON328)-LD30 and ATx631/((TAM428*SV1)*CE151)-LD3 had the highest yields, good exsertion, flowered in good time, and had acceptable plant heights. They also had small grains with good hardness and acceptable whiteness. These two hybrids were compared with regional check varieties

Macia and Tegemeo and they were either superior or within acceptable range for all traits. These two hybrids should therefore be recommended for release in the region.

Hybrids performed better than their open pollinated parents. There is an advantage in growing hybrids over open pollinated varieties as shown by high levels of heterosis for important traits in sorghum. A 37.18% heterosis for yield, 82.77% heterosis for exsertion, -0.02% heterosis for days to mid anthesis and a 23.7% heterosis for height can easily translate to improvement in food security in the semi arid areas of Southern Africa.

Most national programs in the region have the required seed system components in place. These components are: (i) Commercial seed companies with resources to research, produce, process and market seed, (ii) Seed farmers with isolated pieces of land for commercial seed production, (iii) Sorghum grain farmers in drought prone areas who are prepared to purchase hybrid seed if available and (iv) Processors who process the grain to various end products. This research will not be complete if the two recommended hybrids are not promoted to mobilize these various players in the seed system to use this new technology as they are currently doing with other crops.

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